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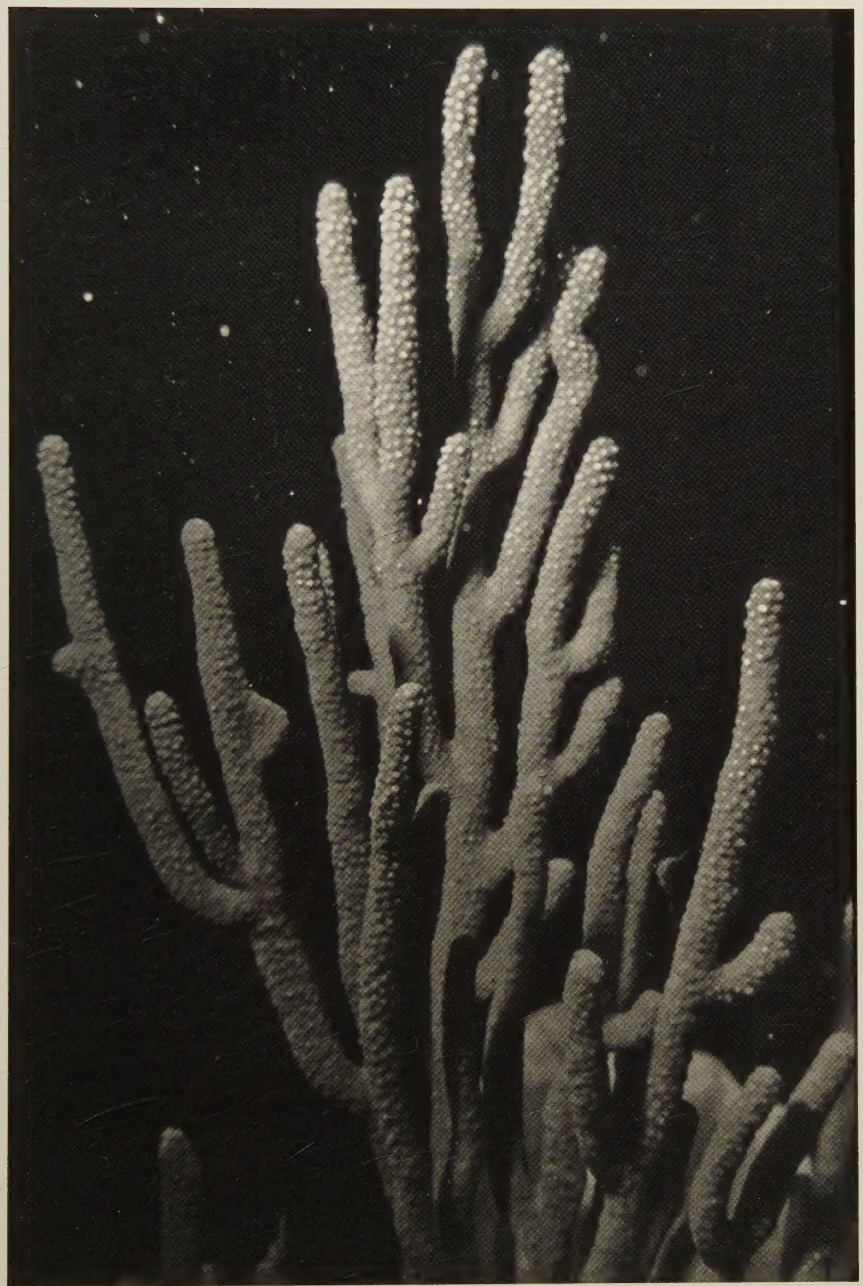

Knobby Sea Rod

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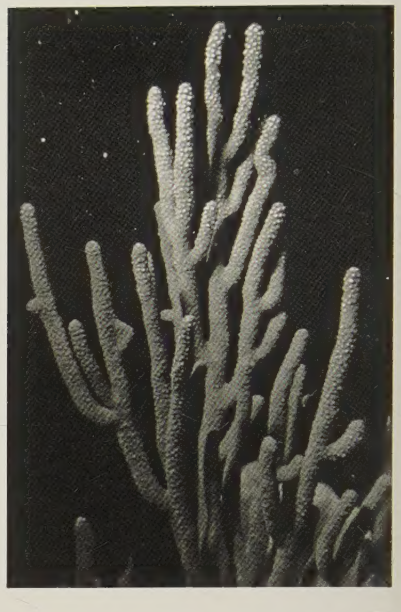

Knobby sea rod in the Florida Keys National Marine Sanctuary. Credit: Florida Keys National Marine Sanctuary Staff; Florida Keys National Marine Sanctuary.

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Deep Fishing: Dream or Disaster?

MEGAN RODDEN and CHARLES W. FOWLER

Introduction

A great deal of emphasis has been placed on the need to be careful about human impact on the world's oceans. International attention is exemplified by targets established by the United Nations[1] in regard to issues such as pollution, marine protected areas, harvesting, and ocean acidification. Elements common to most of the expressed concerns include sustainability and the need to use the best available scientific information for guidance. There has been particular attention paid to harvesting resources at depths greater than observed for most conventional fisheries (e.g., Norse et al., 2012; St. John et al., 2016). The mesopelagic zone (roughly 200–1,000 m in depth) is often characterized by a fish community including many species of Myctophiids (lanternfish) as well as other fish and invertebrates—often small-bodied species (e.g., krill, *Meganyctiphanes norvegica*). The overall complexity with which we are confronted in their evolutionary and ecological interactions is beyond conventional treatment (e.g., see: Merrie et al., 2018); the lack of holism in conventional approaches to management is pervasive.

St. John et al. (2016) cite previous work to indicate that there may be as much as 10 billion metric tons of biomass in mesopelagic communities that could potentially be harvested to help guarantee "sustainable development for our growing human population." Without considering the lack of sustainability for the observed human population, these authors are careful to emphasize the need to bring more holism to any decision. We whole-heartedly agree that holism is imperative, particularly when human participation in ecosystems and the biosphere is in question. We also agree that it is extremely important to bring the best available scientific information to the task—something conventional management fails to do (Fowler et al., 2013).

With this in mind, we take advantage of holistic normative information (Fowler, 2003, 2009; Fowler et al., 2013) to show that harvesting mesopelagic biomass, at depths where it is found, would be abnormal (and therefore unsustainable) for mammalian species of our body size. This deals with depth directly. As a large-scale environmental impact assessment, we extend this process by bringing holism, and the best available scientific

[1] E.g., see the 14 targets listed at https://www.un.org/sustainabledevelopment/oceans/.

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ABSTRACT—A team of European scientists recently raised concerns regarding the potential of harvesting biomass from mesopelagic ecosystems to help sustain the growing human population. They cite research showing that there may be up to 10 billion metric tons of pelagic biomass comprised of species in numerous taxonomic groups living at depths typically between 300 and 800 m—resources infrequently harvested commercially but with both benefits and risks to being harvested. They stressed the need for sustainable harvests, partly to avoid compromising the needs of future generations. They also stressed the need for further assessment, a more holistic understanding of the dynamics of deep-sea communities, and the need to consider the consequences of such harvests.

In this paper, we join this team of scientists in being precautionary—especially in bringing holism to decision making. We take advantage of holistically normative natural patterns for guidance to avoid abnormal consequences of harvesting mesopelagic biomass—consequences involving systems such as other species, marine ecosystems, the marine environment, and the biosphere to include the sustainability of such systems themselves. This involves addressing questions such as "In comparison to other species, would harvesting mesopelagic resources involve abnormality in the depths at which humans harvest from the marine environment?" or "In comparison to other species, would harvesting mesopelagic resources contribute to abnormality in the total harvest currently taken by humans in the marine environment?" We consider other aspects of the human presence and influence on our planet and address observed abnormality as it would be influenced by mesopelagic harvests.

Our approach takes advantage of holistic information important to any aspect of management, and especially harvesting resources. This is information about the participation in complex natural systems by other species. We begin by examining the abnormality that would be involved in taking resources at the depths where mesopelagic communities are observed to occur—to directly address the issue of depth. We then consider both directly and indirectly related dimensions of such harvesting to show how abnormality already observed in human participation in ecosystems and the biosphere would be accentuated. We conclude that it would be a serious mistake to harvest deep-sea resources. Harvesting at such depths would itself be an abnormality in the ways humans participate in marine ecosystems. It would also result in the accentuation or perpetuation of many other forms of abnormality—often already extreme in their magnitude.

information[2], to addressing questions related to other obvious consequences of harvesting mesopelagic biomass. An example of these questions is: "At what rate can we sustainably harvest biomass from the entire marine environment?"—owing to the fact that harvesting mesopelagic biomass would add to harvests that are already being taken from the marine environment. We take advantage of the interconnected nature of reality to carry this process forward to examine the sustainability of other dimensions of being a species involved in harvesting mesopelagic biomass (e.g., energy consumption, CO_2 production, and other direct and indirect consequences of harvesting biomass). Rather than seeking to sustain the human population, we acknowledge the abnormality of our population and strive to avoid perpetuation of management that makes this and associated problems worse (e.g., extinction rates associated with the effects of overpopulation (Gaston, 2005)).

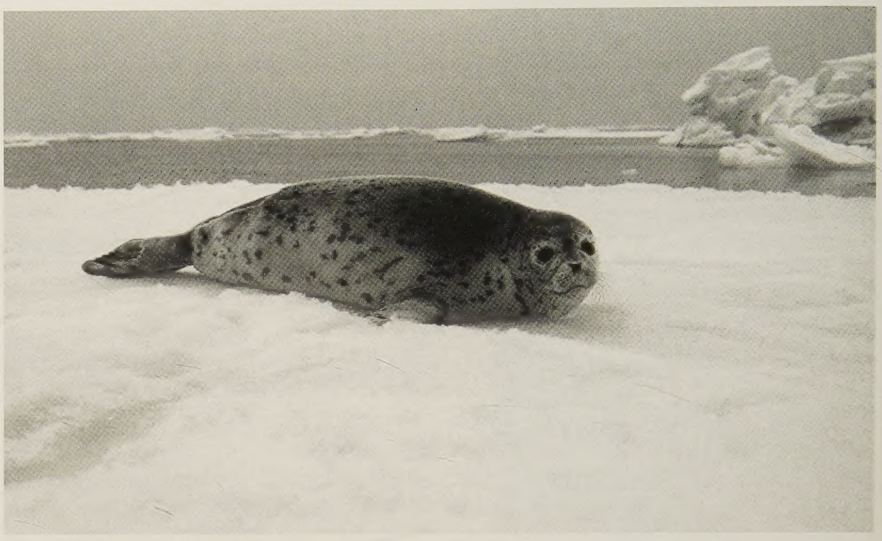

Plate 1.—The spotted seal, *Phoca largh,* is a species that represents mammals of roughly human body size to serve as an example of ecological sustainability for humans to mimic (Photo: Dave Withrow, NOAA).

Methods

In this paper, we drew upon the integrative (holistic, Fowler, 2009; Fowler et al., 2013) nature of information in naturally occurring patterns to assess the sustainability of harvesting resources from mesopelagic communities. The first question we addressed was "At what depths can we sustainably harvest marine resources?" A different way of expressing this question would be "At what depths can we harvest marine resources without engaging in abnormal participation in marine ecosystems?"

To address these questions, we used information that is consonant[3] with the questions, that is, normative information regarding the depths at which marine mammals harvest resources as empirical examples of what works sustainably for mammals[4]—such species have been parts of natural systems for thousands of years and represent empirical examples of sustainability. The information we used was obtained by searching published literature regarding studies of the depths to which marine mammals dive in their foraging behavior. A list of such species was developed, accompanied by data regarding measures of the depths of their dives. Marine mammals are known for their sexual dimorphism; when depths were reported for both males and females of a particular species we used the mean to characterize the species. We recorded data, as available, for both the maximum depths to which dives were recorded as well as the mean depths associated with individual species.

Macroecological patterns often involve metrics that are related to body size (Peters, 1983[5]). In view of the possibility that such patterns include the depth to which mammals dive, it is important to account for body mass directly in any patterns involving the depths at which resources are consumed/harvested. We humans, as a species, have a characteristic body size and this can be accounted for directly, in parallel to accounting directly for taxonomic category through comparing ourselves to mammals in regard to the depths at which we extract biomass. Thus, we also searched the literature, and online resources, for data regarding adult body size for the species of marine mammals represented by estimates of their respective depth of dives. As with data for depth, we used the mean of measurements for males and females to characterize adult body mass for individual species. To achieve consonance regarding size, we assumed that species in the range of one-half to twice the adult body mass of humans were approximately of human size; comparing ourselves (as a species) to large whales, for example, would not be a fair comparison. The refined management question (Hobbs and Fowler, 2008) becomes "At what depths can we, as a mammalian species with our characteristic body size, harvest marine resources without engaging in abnormal participation in marine ecosystems?"

[2] I.e., holistic information consonant[3] with the questions being addressed (Fowler 2003; Fowler et al., 2013).

[3] See Hobbs and Fowler (2008), Fowler (2009), Fowler et al. (2013), and Fowler and Hobbs (2011) for details regarding the concept of consonance.

[4] We are mammals and using such information directly accounts for this taxonomic category for our species as one element of achieving consonance directly.

[5] See also Roth (2014) and references therein.

Our treatment of measurements of other species-level characteristics that involve the consequences of harvesting mesopelagic biomass was based on previously published materials that reveal patterns consonant with the respective management questions.

Results

Figure 1 illustrates the relationship between maximum depth of dives and body size for 51 species of marine mammals (Appendix Table A1.1 contains the results of our compilation of data for depth of dives, and Appendix Table A2.1 contains data for body size). The mean of maximum diving depths is 442 m. The vertical dashes represent body sizes equivalent to half and double the mean adult body size assumed for humans (68 kg). Species characterized by body mass within this range are species with which we can compare our species and avoid the lack of consonance involved in comparing ourselves to species outside of this range.

Figure 2 depicts the frequency distribution of maximum diving depths for the 14 species represented in Figure 1 as species that have adult body sizes that are between half and twice that for humans (i.e., within the range that we have defined to be approximately of human body size).

Figure 3 shows the frequency distribution of Figure 2 in comparison to the depths of mesopelagic biomass identified by St. John et al. (2016), from the second panel of their Figure 2, showing the echogram for the Irminger Sea, as recorded in 2013. We note that the bulk of the biomass shown in this echogram is below the mean of maximum diving depths for marine mammals (235 m). Harvesting this biomass would be a matter of participating in ecosystems like this in ways that would result in measurable abnormality for mammals of our body size and should be avoided.

Figure 4 shows a pattern similar to that of Figure 1, here as measures of mean (rather than maximum) depth of dives, again plotted against estimates of mean adult body mass. As with Figure 1, the upper and lower bounds of mean adult body mass similar to that of humans are identified by the vertical dashed lines. The average mean depth of dives for species (N = 12) of roughly human body mass is 87 m.

Figure 5, otherwise similar to Figure 3, compares the frequency distribution of mean diving depths for mammalian species of roughly human body mass to the depths of biomass observed in the mesopelagic community. Here the abnormality of harvesting at such depths is more obvious as nearly all of the observed mesopelagic biomass is below the 87 m average mean depth

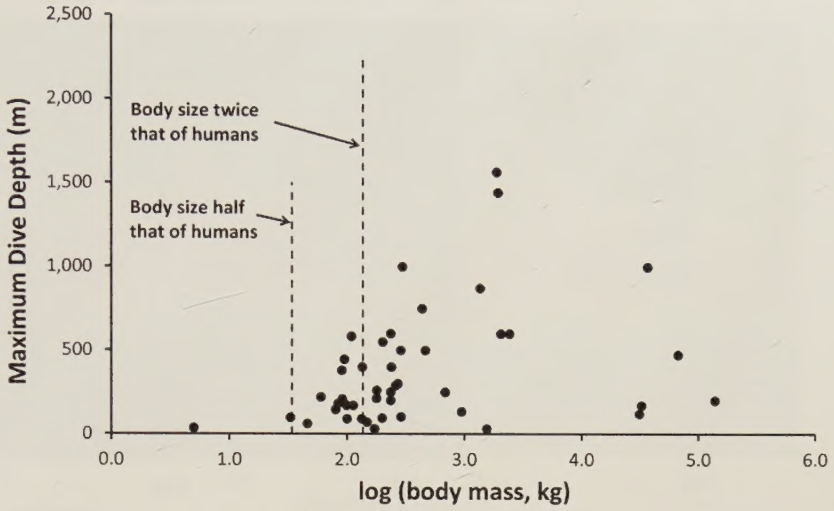

Figure 1.—Pattern among *maximum* diving depths observed for 51 species of marine mammals (Appendix Table A1.1), in relation to mean adult body size (Appendix Table A2.1).

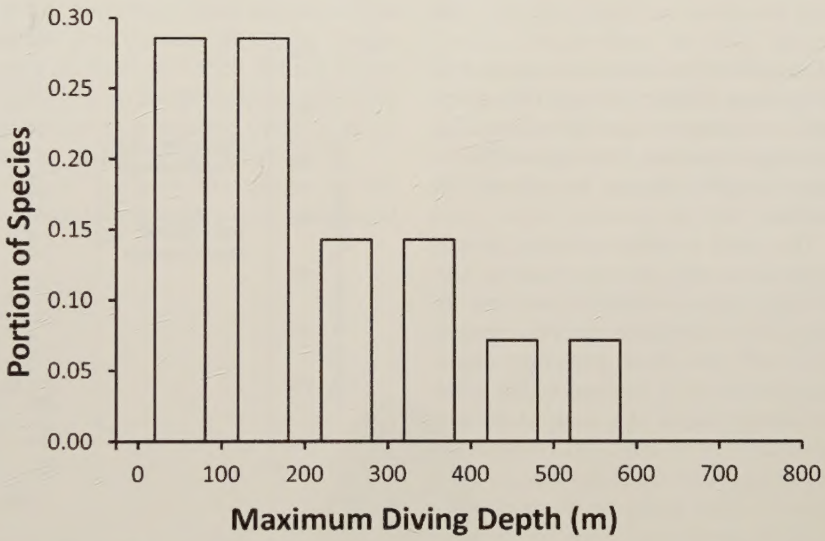

Figure 2.—Frequency distribution of maximum diving depths for the 14 species of marine mammals shown in Figure 1 with adult body sizes that are between half and twice the body size assumed for humans ($\bar{x}$ = 235 m).

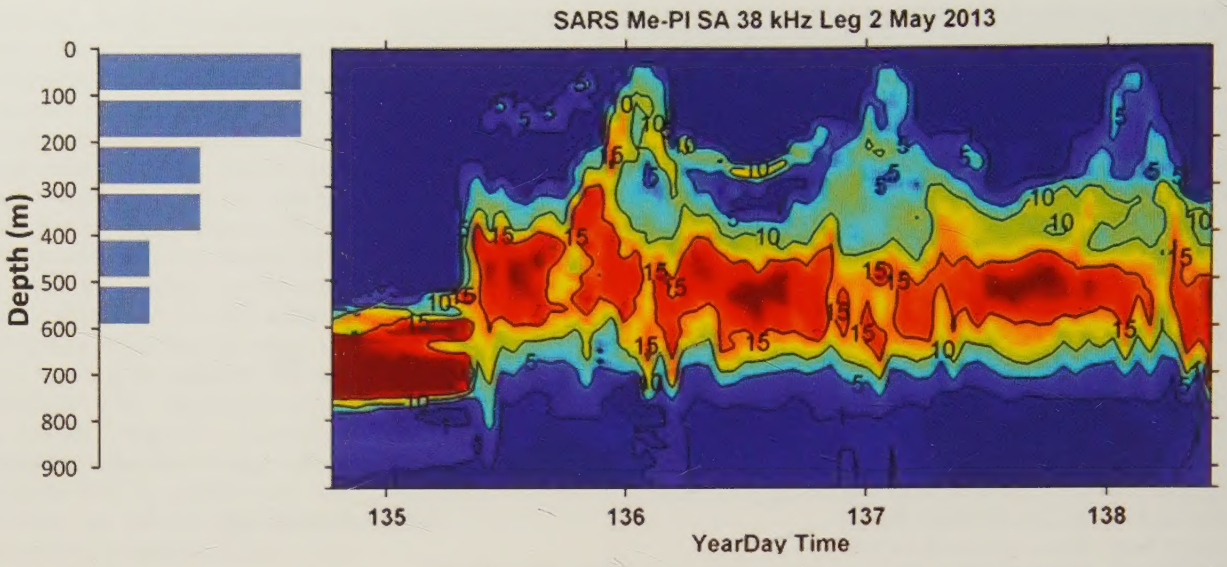

Figure 3.—Histogram of Figure 2 (blue bars in left panel) rotated 90° clockwise to show a comparison of maximum diving depths for marine mammals of approximately human body size with the depths at which mesopelagic biomass occurs (the darker red areas in the right panel show the highest densities of biomass – from Figure 2, page 2, of St. John et al., 2016).

of dives for the marine mammals with body sizes similar to ours. This, by itself, is evidence that harvesting mesopelagic biomass is to be avoided; it would be abnormal to harvest at such depths.

The depth at which harvests are taken involves only one dimension of harvesting marine resources and was the only issue addressed directly, specifically with the results presented above. Another factor of concern is that of the harvesting itself. We must deal with sustainability in the total biomass we humans harvest from the marine environment. This brings us to more management questions. One of primary and obvious relevance is "At what rate can humans sustainably harvest biomass from the marine environment?" (or "At what rate can we harvest marine resources to participate normally in the marine environment?"). Each can be refined to account for factors such as body size. Such questions are important because any harvest of mesopelagic biomass would add to the total of existing harvests of marine biomass by humans.

Figure 6 shows the abnormality of harvests of marine biomass by humans in the late 1900s in comparison to that of 15 other species of mammals with body mass roughly similar to that of humans. In this graph, there are three components. The pie chart in part A is an illustration of the diversity of rates at which marine mammals of our body size are estimated to have consumed biomass from the world's oceans. The area of this chart is equivalent to that of the section of the chart in part B that represents the nonhuman species (with colors identical to those in part A); the total area of both charts is proportional to the total take in each case, with humans making up the red component of the larger chart. In part C, the abnormality apparent in part B is revealed in a histogram (with log

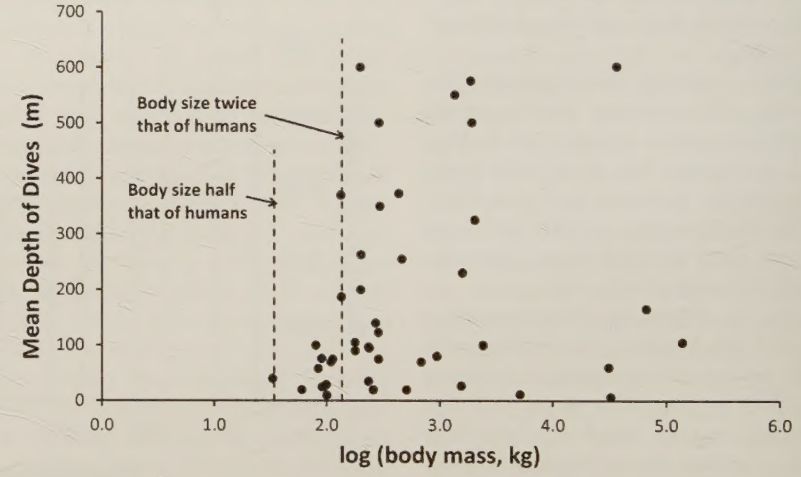

Figure 4.—Pattern of mean diving depths, as observed for 45 species of marine mammals, in relation to mean adult body size (as based on data from Appendix Tables A1.1 and A2.1).

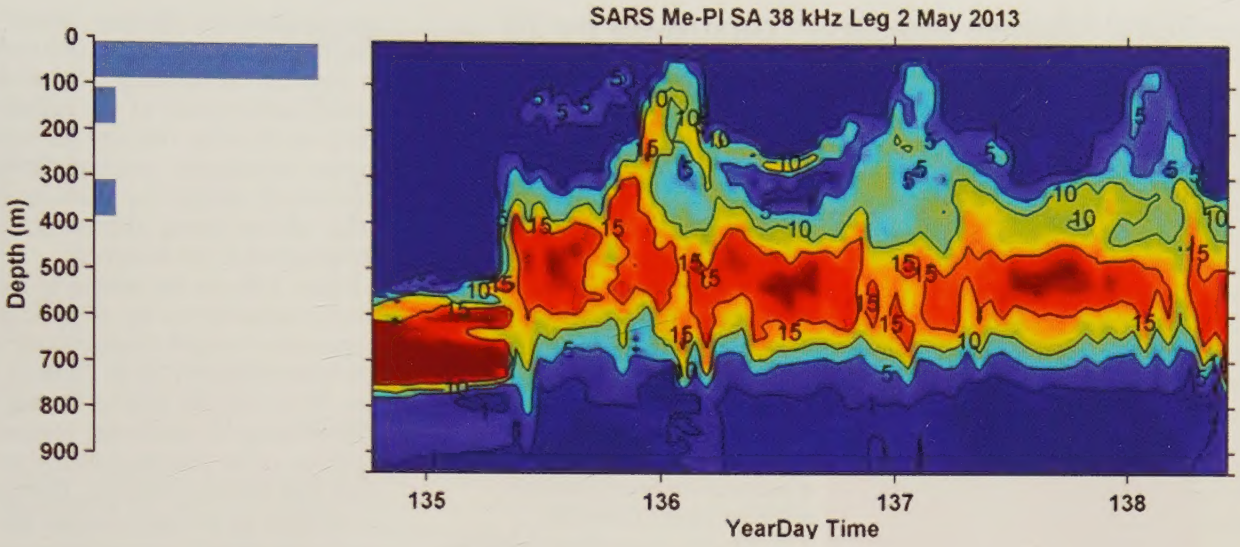

Figure 5.—Comparison of mean diving depths for 12 species of marine mammals of roughly human body mass to the depths of mesopelagic biomass (see Figure 3). ($\bar{x}$ = 87 m for mean depth of dives).

transformation of the data used in the pie charts) revealing the harvest by humans to be an outlier. The harvest by humans was over 61-fold larger than the mean among the other species. Clearly, the biodiversity of this consumer/resource system is compromised by the dominance of humans. Maximizing the biodiversity of this system (following procedures described by Fowler (2008)) would have required reducing the harvest by more than 97%. Assuming that an abnormality of this magnitude is observed currently, adding a harvest of biomass from the mesopelagic resources identified by St. John et al. (2016) would obviously accentuate the inherent and related problem(s) and is, by itself, also basis for rejecting any proposal to harvest more mesopelagic biomass.

Marine protected areas are another facet of management in harvesting from the marine environment. Harvesting mesopelagic biomass would do nothing to reduce the area of the Earth's oceans that are subjected to harvests (one direct anthropogenic impact); it would likely result in an increase. This gives rise to the management question: "What portion of the marine environment should be areas in which harvesting is prohibited?" For our purposes "What portion of the marine environment should be designated as areas in which fishing is not allowed so as to participate normally (sustainably) in oceanic systems in regard to marine protected areas?"

Figure 7 shows the results of addressing this question with empirical data. We used data for estimated geographic range sizes for 102 species of marine mammals (as published by Pompa et al., 2011; see Appendix 3, Table A3.1). The mean percent of the world's oceans left unoccupied by the 40 species of roughly human body mass (again bounded by the two ver-

Plate 2.—The gray whale, *Eschrichtius robustus*, is a species that represents mammals but with a body size too large to be considered similar to humans; as a species, it does not necessarily serve well as an example of ecological sustainability for humans to mimic (Photo: C. W. Fowler).

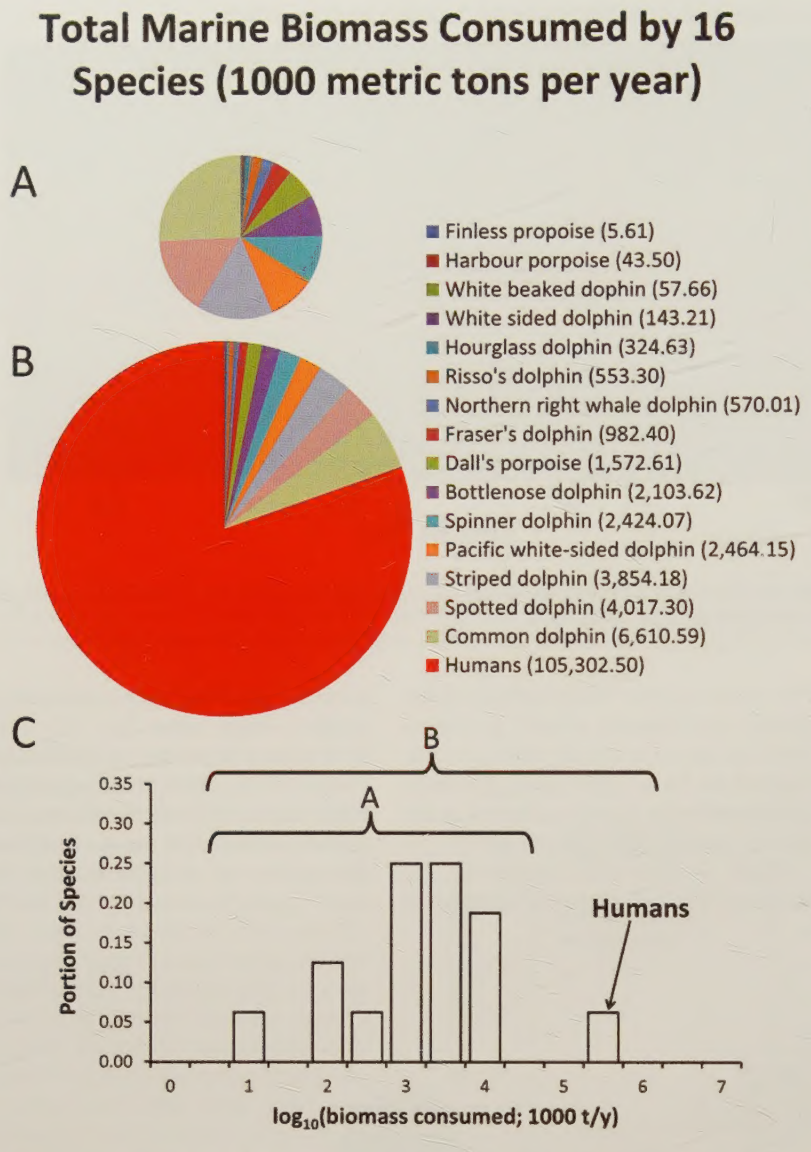

Figure 6.—Comparison of the total annual harvests of biomass from the marine environment by humans for the late 1900s compared to the pattern in consumption by 15 species of marine mammals similar in size to humans, based on data used by Fowler and McCluskey (2011).

tical dashed lines) is 98.7%, based on logit transformed data. Humans are undoubtedly already harvesting from more than 1.3% of the marine environment (see Appendix 3)[6]. Adding any additional area needed to harvest mesopelagic biomass would again accentuate an extreme human abnormality and be grounds for concluding that we should not harvest these resources.

Another consequence[7] of harvesting mesopelagic biomass would be the consumption of energy. This would include energy needed to conduct the harvest, transport catches, process for consumption (either directly by humans or domestic species), delivery of resulting products to stores and homes, as well as the manufacture, maintenance, and disposal of the equipment involved. At what rate can the human species sustainably consume energy? How much energy can humans consume without being abnormal in our participation in the biosphere?

Figure 8 shows the pattern in global energy consumption by 64 species of mammals of roughly human body size (including humans). As in Figure 6, the area of the tiny pie chart at the top left (representing 63 nonhuman species) is the same as the miniscule wedge in the chart that includes humans. This chart is enlarged on the right so that the diversity in rates of consumption among the nonhuman species can be seen. Both the pie chart including humans and the histogram of log transformed data below illustrate the abnormality that would be accentuated by the additional energy consumption associated with taking and using biomass from the mesopelagic community. The consumption of energy by humans is already over 20,000 times greater than the mean rate of consumption by other species of roughly human body mass (Fowler, 2008). Harvesting mesopelagic biomass would escalate this abnormality; additional harvests from the marine environment of any kind are ill-advised.

Energy consumption, of course, often involves burning fossil fuels with emissions that include carbon dioxide. Comparison of CO_2 production by humans to that of other species (Fowler and Oppenheimer, 2017) results in observing abnormality very similar to that for total energy consumption (Fig. 8). As with all of the abnormalities treated above, removing biomass from mesopelagic communities would amplify the abnormality of anthropogenic CO_2 production and all of its consequences (including ocean acidification)—already orders of magnitude larger than normal for mammalian species of our body size (Fowler, 2008). Alone, but especially in combination with other abnormalities, accentuated atypical CO_2 production

[6] Jones et al. (2018) indicate that only 6.97% of the world's oceans are designated marine protected areas.

[7] Holistically, there may be an infinite set of such consequences.

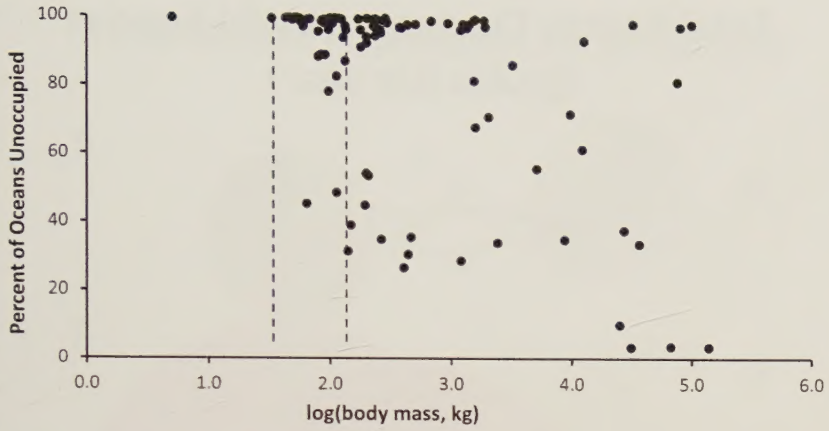

Figure 7.—Illustration of the pattern for the percent of the world's oceans that are not occupied by 102 species of marine mammals as related to body mass (with dashed lines showing limits to the range of species of body sizes similar to that of humans as in Fig. 1 and 4). See text and Appendix 3 for details.

caused by harvesting mesopelagic biomass again leads to the conclusion that it is to be avoided.

Finally, St. John et al. (2016) reconize a connection between food consumption and the human population. Attempts to find resources to feed the human population require that we ask the question: "How large is a sustainable human population?" What human population would be of normal size in comparison to the populations of other mammals of our body size? Figure 9 displays the abnormality of our population; continuing to provide food to feed this population is another example of maintaining the status quo when it is not holistically sustainable. The human population is currently orders of magnitude larger than central tendencies among nonhuman species of mammals with body sizes similar to ours (Fowler, 2008, 2009), and providing more food would tend to induce further growth, ultimately magnifying this abnormality and its consequent problems. Maintaining abnormality in any of the ways we participate pathologically in nature is to be avoided; their consequences count among the problems observed globally. In particular, we conclude that the harvest of biomass from mesopelagic communities should be avoided.

Discussion

The results of our work involve only a very small sample of abnormalities in our species' participation in the natural world, particularly in the marine environment. Harvesting biomass from the mesopelagic community would bring about innumerable forms of additional influence on communities at depths that would be abnormal if done by any mammalian species of our body size. Thus, the depth that such harvesting would involve is, by itself, basis for rejecting any suggestion to harvest such biomass.[8] Owing to the interconnected nature of reality, however, the list of related unsustainable (abnormal) participatory modes of human existence extends well beyond depth (Fig. 5) to include total marine biomass consumption (Fig. 6), portions of the Earth used for extracting resources (Appendix 3), global energy consumption (Fig. 8), CO_2 production, and population size (Fig. 9). Harvesting mesopelagic biomass would almost certainly accentuate them all, including those beyond the scope of this paper and involving the innumerable components of all systems that would be impacted—directly, indirectly, now or later.

Even among known examples of abnormality, the sample above is small. The numerous ways in which we ex-

[8] A complete and distinct scientific paper could have focused on this issue alone.

Plate 3.—The howler monkey, *Alouatta palliata*, is a species that represents mammals but with a body size too small to be considered similar to humans; as a species, it does not necessarily serve well as an example of ecological sustainability for humans to mimic (Photo: C. W. Fowler).

hibit abnormality (pathological participation or lack of sustainability) are seen in measures that often involve several orders of magnitude (Fowler and Hobbs, 2003; Fowler, 2008, 2009). Although fisheries management has resulted in confining abnormality in the rates of harvesting to about one or two orders of magnitude (Fig. 6, Fowler et al., 2013; Darimont et al., 2015), harvesting mesopelagic biomass would clearly accentuate these problems. Beyond the simple issue of harvest rates, it is important to recognize that existing fisheries already contribute to the abnormality of things like energy consumption, carbon dioxide production, and overpopulation. In other words, the abnormal fishing observed in total takes from the marine environment (Fig. 6) is, without adding to it, already contributing to other forms of abnormality for our species—abnormality that would be magnified by harvesting mesopelagic biomass.

The full collection of abnormalities associated with human overpopulation is important to realize. The examples illustrated above are no more than a small sample; any management to maintain the status quo retains all of the impacts involved. Most of these impacts will probably remain unknown to science, but include things like the human impact on water supplies and ecosystems such as rivers and lakes, some of which have been completely destroyed already. Water consumption by humans counts among the examples of abnormality that are measured in orders of magnitude (Fowler, 2008). The abnormality of our population size is expressed in many indirect effects, including extinction (e.g., McKee et al., 2013; even the risk of our own), global warming, ocean acidification, and pollution (all to the extent, and in the ways, that population is actually involved). Thus, arguments to the effect that we need to consider harvesting mesopelagic biomass to feed the human population is a matter of maintaining the status quo when what we observe is abnormal and, therefore, not sustainable—not for humans, not for other species, not for their ecosystems, and not for the biosphere. These are all systems with which we interact and, for sustainability (both for theirs and ours), require sustainable interactions, participation, and consequences.

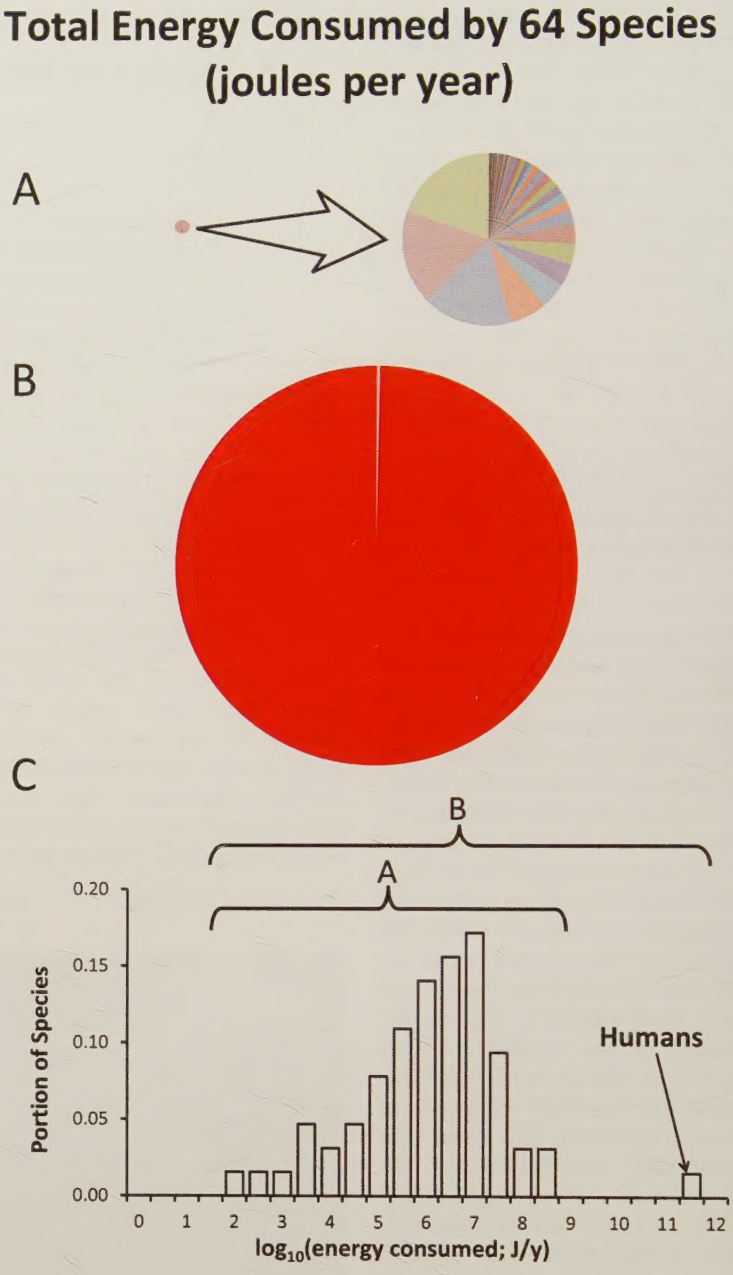

Figure 8.—Graphic representation of the pattern for annual energy consumption by 64 species of mammals of roughly human body mass illustrating the abnormality of consumption by humans (see Fowler, 2008).

When faced with options like those brought to our attention by St. John et al. (2016), we have the challenge of assessing environmental impacts holistically. From the perspective of the holistic approach we have brought to bear in this paper, any action we consider (any management decision) needs

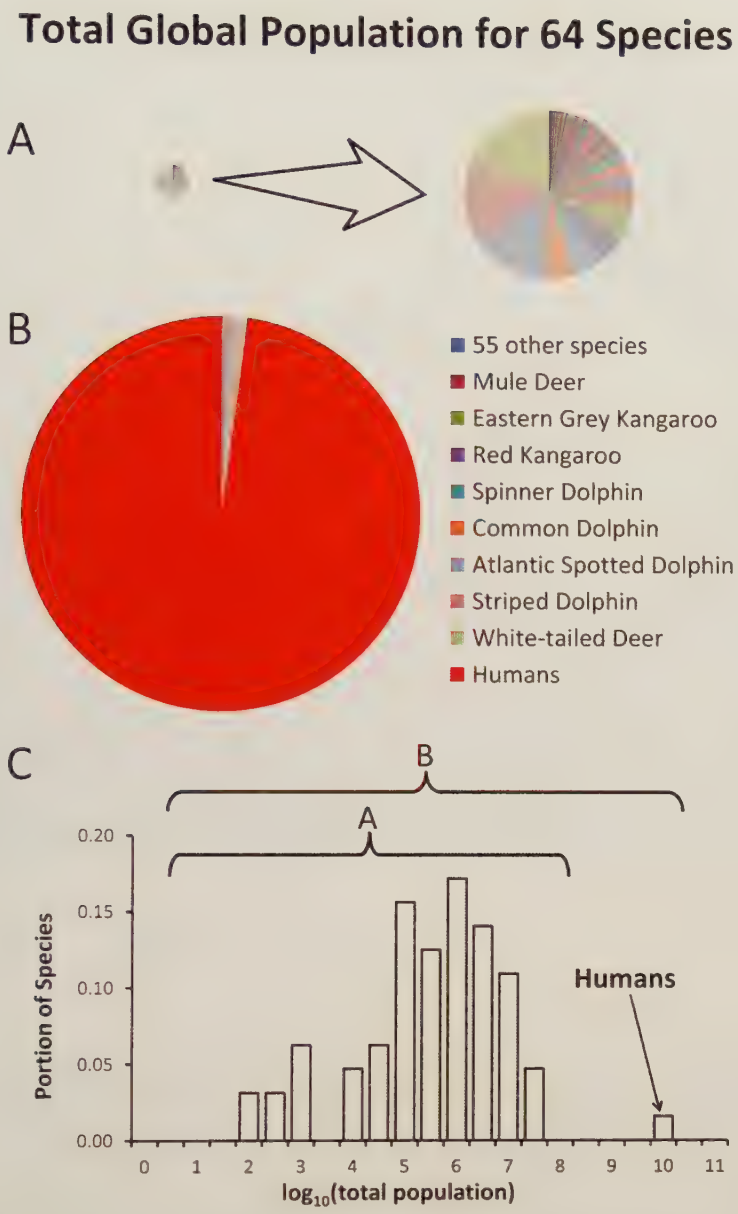

Figure 9.—Human population in comparison to the pattern for population size among 63 species of mammals of roughly human body mass (see Fowler, 2008).

to be treated consistently—consistency achieved by avoiding abnormality or ecologically pathological participation or interactions with the nonhuman. Cases of environmental impacts which would lead to prolonged or accentuated abnormality are cases for rejecting proposed management action. Holistically, this prevents factors such as human greed, anthropocentrism, genetic predisposition, economics, politics, opinions, emotions, and values from driving us further into trouble by perpetuating or accentuating problems of the kinds already faced in today's world.

Norse et al. (2012) provide conventional arguments against fishing from the deep sea. Their approach is of the kind St. John et al. (2016) presumably had in mind in their advice to "guarantee a sustainable exploitation of these resources" to achieve more holism in the assessment and understanding of mesopelagic communities. The perspective behind our work involves the understanding that each identifiable component of such harvests can be dealt with in a completely holistic manner (Fowler, 2003, 2009; Fowler et al., 2013; Fowler et al., 2014); but we extend this to include larger management questions involving whether or not to take such a harvest at all. We hasten to emphasize, however, that a large part of the infinite set of management questions confronting our species remains beyond our grasp; only those management questions that we find it possible to ask can be addressed holistically (Hobbs and Fowler, 2008).

As such, we fully support St. John et al. (2016) in their advice to achieve holism in considering the potential of harvesting mesopelagic biomass. A great deal of holism is brought to the task in every way we can compare ourselves with other similar species (Hobbs and Fowler, 2008; Fowler, 2009; Fowler et al., 2013) and, through such comparisons, we find that human abnormality would be intensified in virtually all cases. The importance of avoiding ecologically pathological forms of impact on systems of which we are a part seems obvious. Otherwise, sustainability at all levels is compromised rather than achieved—including all temporal, spatial, and hierarchical scales. We conclude that it would be a serious mistake to harvest mesopelagic biomass owing to the perpetuation and accentuation of ways in which humans participate abnormally in the natural world and the consequential abnormality among other species, ecosystems, and the biosphere.

Summary

This paper is not only an example of an environmental impact statement at the global level; it also provides another example of using information consonant with management ques-

Plate 4.—The Delicate Arch (Arches National Park, U.S.) is found in a setting that reveals geological time scales as taken into account through the integrative holism of empirically observed phenomena (Fowler et al., 2013) exemplified by the normative patterns in this paper (Photo: C. W. Fowler).

tions—the best scientific information for guidance as well as evaluation. One aspect of the holism of such information involves its being applicable to any management question we are capable of asking. Our evaluation of the potential for harvesting biomass from mesopelagic communities (characterized by St. John et al., 2016) involves just one small set of examples wherein the application of such information is possible. However such information is applied, it involves a form of holism that is impossible in conventional approaches to decision making. Holism is made possible by the naturally integrative form of information embodied in patterns among species with which we can appropriately compare humans. In all of the ways we make such comparisons, we find that harvesting mesopelagic biomass would aggravate anthropogenic abnormality.

The list of abnormalities for this case begins with the depths at which harvests would be taken. The set of pathological influences goes beyond this to include the area of oceans subjected to harvesting, total global marine harvest rates, consumption of energy, production of carbon dioxide, and overpopulation. The higher-order consequences of these forms of pathological impact are to be avoided. They are not sustainable for any of the living systems involved. We conclude that the dream of harvesting mesopelagic biomass would be a disaster; it is imperative that we reverse (rather than extend) our tendency to either maintain or accentuate pathological existence in the natural world.

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Appendix 1

Depth of Dive Information for Marine Mammals

Appendix Table A1.1 shows a list of marine mammal species (following nomenclature used by Pompa et al., 2011) for which we found information regarding the depths to which these species have been observed to dive. As for data regarding body mass (Appendix 2), we used the mean of measures of diving depths for any species with data from multiple sources; this often involved combinations of data for both sexes. As can be seen, a large portion of our data was obtained from the second edition of the Encyclopedia of Marine Mammals (Perrin et al., 2009). From this source, many sets of valuable data were found in the accounts for individual species by various specialists; however a significant portion of the data we used came from Stewart's (2009) account dealing directly with diving behavior.

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Table A1.1.—List of species of marine mammals for which there is information on the depths to which they dive while foraging, showing information for both the mean depths to which they dive and the maximum depths to which they have been observed to dive.

Species	Mean depth of dive (m)	Max. dive depth (m)	Sources
Arctocephalus australis	29	170	Campagna (2008)
Arctocephalus forsteri	76	380	Campagna (2008); Perrin et al. (2009)
Arctocephalus galapagoensis		61	Perrin et al. (2009)
Arctocephalus gazelle	58	181	Perrin et al. (2009)
Arctocephalus philippii	10	90	Perrin et al. (2009)
Arctocephalus pusillus	75	102	Perrin et al. (2009)
Arctocephalus tropicalis	25	208	Perrin et al. (2009)
Balaenoptera musculus	105	200	Perrin et al. (2009)
Balaenoptera physalus	165	474	Perrin et al. (2009)
Callorhinus ursinus	187	400	Perrin et al. (2009)
Cystophora cristata	350	1,000	Perrin et al. (2009)
Delphinapterus leucas	550	872	Perrin et al. (2009)
Delphinus capensis		200	Perrin et al. (2009)
Delphinus delphis	90	260	Perrin et al. (2009)
Dugong dugon		20	Perrin et al. (2009)
Enhydra lutris	40	97	Estes (1980)
Erignathus barbatus	20	288	Perrin et al. (2009)
Eschrichtius robustus	7	170	Perrin et al. (2009)
Eumetopias jubatus	70	250	Perrin et al. (2009); Merrick et al. (1994)
Globicephala macrorhynchus	100	600	Perrin et al. (2009)
Globicephala melas	325	600	Perrin et al. (2009)
Halichoerus grypus	140	300	Perrin et al. (2009)
Lagenodelphis hosei		600	Perrin et al. (2009)
Leptonychotes weddellii	373	750	Perrin et al. (2009)
Lobodon carcinophaga	35	600	Perrin et al. (2009); Hückstädt (2015)
Lontra feline		35	Larivière (1998)
Megaptera novaeangliae	60	120	Perrin et al. (2009)
Mirounga angustirostris	575	1,567	Perrin et al. (2009)
Mirounga leonine	500	1,444	Perrin et al. (2009)
Monachus monachus		500	Perrin et al. (2009)
Neomonachus schauinslandi	263	550	Perrin et al. (2009)
Neophoca cinerea		30	Perrin et al. (2009)
Odobenus rosmarus	80	133	Perrin et al. (2009)
Ommatophoca rossii	105	212	Perrin et al. (2009)
Orcinus orca		12	Perrin et al. (2009)
Otaria byronia	97	250	Perrin et al. (2009)
Pagophilus groenlandicus	370	90	Perrin et al. (2009)
Phoca vitulina	26	446	Perrin et al. (2009)
Phocarctos hookeri	123	500	Perrin et al. (2009)
Phocoena phocoena	20	220	Perrin et al. (2009)
Phocoenoides dalli		94	Perrin et al. (2009)
Physeter macrocephalus	600	1,000	Perrin et al. (2009)
Pseudorca crassidens		230	Perrin et al. (2009)
Pusa hispida	100	145	Perrin et al. (2009)
Stenella attenuate	75	170	Perrin et al. (2009)
Steno bredanensis		70	Perrin et al. (2009)
Trichechus manatus	27	30	Perrin et al. (2009)
Tursiops aduncus		200	Perrin et al. (2009)
Tursiops truncatus	255	500	Perrin et al. (2009)
Zalophus californianus	95	400	Aurioles-Gamboa et al. (2015)
Zalophus wollebaeki	70	584	Trillmich (2015)
Ziphius cavirostris		1,888	Perrin et al. (2009)

Appendix 2

Adult Body Mass Estimates for Marine Mammals

Table A2.1 contains a list of 102 species of marine mammals with nomenclature used by Pompa et al. (2011) in their treatment of conservation as related to range size (See Appendix 3). This set of species was selected based in the availability of data for adult body mass. The purpose of this appendix is to document these data and their sources along with the methods we used in deriving the values contained in this table (estimates that were used in both our consideration of diving depths (Appendix 1) and unoccupied portions of various areas of the Earth (Appendix 3)). As can be seen in this table, the bulk of the data for body mass involved information from Perrin et al. (2009), Fowler and Perez (1999), Clauset (2013), and a website maintained by NOAA's National Marine Fisheries Service (https://www.fisheries.noaa.gov/find-species). Sources from Perrin et al. (2009) usually involved species-specific accounts authored by specialists familiar with the species listed.

Marine mammals are known for their sexual dimorphism. To the best of our ability, we used data that are reflective of the mean among males and females. When ranges were reported for either sex, we chose the midpoint.

When there were data from more than one source, we used the mean. In cases where we found data for body size from three or more sources, we removed estimates (13 cases) that resulted in a range larger than half of the original mean; in some cases the data rejected involved what appeared to be estimates that were too large, and in other cases measurements that appeared to be too small. For example, the estimate from Fowler and Perez (1999) for *Sousa chinensis* was 85 kg. This was rejected in light of two other estimates that were very similar to each other (265 from Perrin et al. (2009) and 257 from Clauset (2013)) and, for this species, Fowler and Perez (1999) was not included in the sources list.

In all cases, we are mindful of variance related to factors such as the definition of adult status, sample size, geographic variability, and human error. Also, information from the sources we have used can easily have been based on the same original research. Clearly, there are imperfections that need to be addressed in future research and we emphatically support continued efforts to supply reliable estimates of adult body mass for as many species as possible.

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Table A2.1.—List of species from Pompa, et al. (2011) for which information regarding body mass was found in the literature.

Species	Body mass (kg)	log(body mass, kg)	Sources
Arctocephalus australis	99	1.996	Campagna (2008); Fowler and Perez (1999)
Arctocephalus forsteri	90	1.954	Campagna (2008); Fowler and Perez (1999)
Arctocephalus galapagoensis	46	1.663	Fowler and Perez (1999); Perrin et al. (2009)
Arctocephalus gazella	84	1.924	Fowler and Perez (1999); Perrin et al. (2009)
Arctocephalus philippii	100	2.000	Fowler and Perez (1999); Perrin et al. (2009); NMFS
Arctocephalus pusillus	288	2.459	Fowler and Perez (1999); Perrin et al. (2009)
Arctocephalus townsendi	101	2.004	Perrin et al. (2009); NMFS
Arctocephalus tropicalis	91	1.959	Fowler and Perez (1999); Perrin et al. (2009)
Balaena mysticetus	80,669	4.907	Fowler and Perez (1999); NMFS; Jefferson et al. (1993); Clauset (2013)
Balaenoptera acutorostrata	12,234	4.088	Fowler and Perez (1999); Jefferson et al. (1993); Clauset (2013)
Balaenoptera bonaerensis	8,709	3.940	Fujise et al. (1993); Lockyer (1976)
Balaenoptera borealis	25,000	4.398	Fowler and Perez (1999); Perrin et al. (2009); Clauset (2013)
Balaenoptera edeni	27,228	4.435	Fowler and Perez (1999); NMFS; Jefferson et al. (1993); Clauset (2013)
Balaenoptera musculus	138,573	5.142	Fowler and Perez (1999); Perrin et al. (2009); Clauset (2013)
Balaenoptera physalus	66,761	4.825	Fowler and Perez (1999); Perrin et al. (2009); NMFS; Clauset (2013)
Berardius arnuxii	9,733	3.988	Fowler and Perez (1999); Jefferson et al. (1993); Clauset (2013)
Berardius bairdii	12,647	4.102	Fowler and Perez (1999); Jefferson et al. (1993); Clauset (2013)
Callorhinus ursinus	135	2.130	Fowler and Perez (1999); Perrin et al. (2009)
Caperea marginata	3,227	3.509	Fowler and Perez (1999); Jefferson et al. (1993); Clauset (2013)
Cephalorhynchus commersonii	65	1.813	Fowler and Perez (1999); Jefferson et al. (1993); Clauset (2013)
Cephalorhynchus eutropia	55	1.740	Fowler and Perez (1999); Jefferson et al. (1993); Clauset (2013)
Cephalorhynchus heavisidii	56	1.748	Fowler and Perez (1999); Jefferson et al. (1993); Clauset (2013)
Cephalorhynchus hectori	51	1.708	Fowler and Perez (1999); Jefferson et al. (1993); Clauset (2013)
Cystophora cristata	295	2.470	Fowler and Perez (1999); Perrin et al. (2009); NMFS
Delphinapterus leucas	1,355	3.132	Fowler and Perez (1999); Perrin et al. (2009); NMFS; Clauset (2013)

Table Continued

Table A2.1.—Continued.

pecies	Body mass (kg)	log(body mass, kg)	Sources
Delphinus capensis	235	2.371	Perrin et al. (2009)
Delphinus delphis	179	2.253	Perrin et al. (2009); NMFS; Clauset (2013)
Dugong dugon	508	2.706	Fowler and Perez (1999); Jefferson et al. (1993)
Enhydra lutris	33	1.519	Fowler and Perez (1999); Estes (1980)
Erignathus barbatus	258	2.412	Fowler and Perez (1999); Perrin et al. (2009); NMFS
Eschrichtius robustus	32,417	4.511	Perrin et al. (2009); NMFS; Clauset (2013)
Eubalaena australis	76,110	4.881	Jefferson et al. (1993); Clauset (2013)
Eubalaena japonica	100,000	5.000	Perrin et al. (2009)
Eumetopias jubatus	686	2.836	Fowler and Perez (1999); Perrin et al. (2009)
Feresa attenuata	194	2.288	Fowler and Perez (1999); Jefferson et al. (1993); Clauset (2013)
Globicephala macrorhynchus	2,416	3.383	Fowler and Perez (1999); NMFS; Jefferson et al. (1993); Clauset (2013)
Globicephala melas	2,039	3.309	Fowler and Perez (1999); Jefferson et al. (1993); Clauset (2013)
Grampus griseus	405	2.607	Fowler and Perez (1999); NMFS; Jefferson et al. (1993); Clauset (2013)
Halichoerus grypus	271	2.433	Fowler and Perez (1999); Perrin et al. (2009); NMFS
Histriophoca fasciata	85	1.929	Perrin et al. (2009); NMFS
Hydrurga leptonyx	374	2.573	Fowler and Perez (1999); Perrin et al. (2009)
Kogia breviceps	440	2.643	Fowler and Perez (1999); Perrin et al. (2009); NMFS; Clauset (2013)
Kogia sima	264	2.422	Fowler and Perez (1999); Perrin et al. (2009); NMFS; Clauset (2013)
Lagenodelphis hosei	198	2.297	Perrin et al. (2009); NMFS; Clauset (2013)
Lagenorhynchus acutus	228	2.358	Fowler and Perez (1999); Perrin et al. (2009); NMFS; Clauset (2013)
Lagenorhynchus albirostris	237	2.375	Fowler and Perez (1999); Perrin et al. (2009); NMFS; Clauset (2013)
Lagenorhynchus australis	116	2.064	Fowler and Perez (1999); Perrin et al. (2009); Clauset (2013)
Lagenorhynchus cruciger	113	2.053	Fowler and Perez (1999); Perrin et al. (2009); Clauset (2013)
Lagenorhynchus obliquidens	128	2.107	Fowler and Perez (1999); Perrin et al. (2009); NMFS; Clauset (2013)
Lagenorhynchus obscurus	104	2.017	Fowler and Perez (1999); Perrin et al. (2009); Clauset (2013)
Leptonychotes weddellii	435	2.638	Fowler and Perez (1999); Perrin et al. (2009)
Lissodelphis borealis	97	1.987	Fowler and Perez (1999); Perrin et al. (2009); NMFS; Clauset (2013)
Lissodelphis peronii	97	1.987	Fowler and Perez (1999); Perrin et al. (2009); Clauset (2013)
Lobodon carcinophaga	235	2.371	Fowler and Perez (1999);
Lontra felina	5	0.699	Larivière (1998)
Megaptera novaeangliae	31,084	4.493	Fowler and Perez (1999); Jefferson et al. (1993); Clauset (2013)
Mesoplodon carlhubbsi	1,584	3.200	Jefferson et al. (1993); Clauset (2013)
Mesoplodon densirostris	1,208	3.082	NMFS; Jefferson et al. (1993); Clauset (2013)
Mesoplodon europaeus	1,200	3.079	NMFS; Jefferson et al. (1993)
Mesoplodon grayi	1,550	3.190	Jefferson et al. (1993); Clauset (2013)
Mesoplodon mirus	1,414	3.150	NMFS; Jefferson et al. (1993); Clauset (2013)
Mirounga angustirostris	1,875	3.273	Fowler and Perez (1999); Perrin et al. (2009)
Mirounga leonina	1,920	3.283	Fowler and Perez (1999); Perrin et al. (2009)
Monachus monachus	290	2.462	Fowler and Perez (1999); Perrin et al. (2009); NMFS
Monodon monoceros	1,256	3.099	Fowler and Perez (1999); Perrin et al. (2009); Clauset (2013)
Neomonachus schauinslandi	201	2.303	Fowler and Perez (1999); Perrin et al. (2009); NMFS
Neophoca cinerea	171	2.233	Fowler and Perez (1999); Perrin et al. (2009)
Neophocaena phocaenoides	57	1.756	Fowler and Perez (1999); Perrin et al. (2009); Clauset (2013)
Odobenus rosmarus	944	2.975	Fowler and Perez (1999); Perrin et al. (2009)
Ommatophoca rossii	178	2.250	Fowler and Perez (1999); Perrin et al. (2009)
Orcaella heinsohni	124	2.093	Perrin et al. (2009)
Orcinus orca	5,115	3.709	Fowler and Perez (1999); Perrin et al. (2009); Clauset (2013)
Otaria byronia	235	2.371	Fowler and Perez (1999); Hückstädt (2015)
Pagophilus groenlandicus	133	2.124	Perrin et al. (2009); NMFS
Peponocephala electra	207	2.316	Fowler and Perez (1999); Perrin et al. (2009); NMFS; Clauset (2013)
Phoca largha	88	1.944	Fowler and Perez (1999); NMFS
Phoca vitulina	95	1.978	Fowler and Perez (1999); Perrin et al. (2009); NMFS
Phocarctos hookeri	286	2.456	Fowler and Perez (1999); Perrin et al. (2009)
Phocoena dioptrica	86	1.934	Fowler and Perez (1999); Perrin et al. (2009)
Phocoena phocoena	60	1.778	Fowler and Perez (1999); Perrin et al. (2009); NMFS; Clauset (2013)
Phocoena sinus	53	1.724	Fowler and Perez (1999); NMFS; Jefferson et al. (1993); Clauset (2013)
Phocoena spinipinnis	68	1.833	Fowler and Perez (1999); Perrin et al. (2009); Clauset (2013)
Phocoenoides dalli	199	2.299	Perrin et al. (2009); NMFS; Clauset (2013)
Physeter macrocephalus	36,433	4.561	Fowler and Perez (1999); Perrin et al. (2009); Clauset (2013)
Pontoporia blainvillei	43	1.633	Perrin et al. (2009); Clauset (2013)
Pseudorca crassidens	1,587	3.201	Fowler and Perez (1999); Clauset (2013)
Pusa hispida	80	1.903	Perrin et al. (2009); NMFS
Sotalia fluviatilis	49	1.690	Perrin et al. (2009); Clauset (2013)
Sousa chinensis	261	2.417	Perrin et al. (2009); Clauset (2013)
Sousa teuszii	228	2.358	Perrin et al. (2009); Clauset (2013)
Stenella attenuata	113	2.053	Fowler and Perez (1999); Perrin et al. (2009); NMFS; Clauset (2013)
Stenella clymene	80	1.903	NMFS; Jefferson et al. (1993); Clauset (2013)
Stenella coeruleoalba	140	2.146	Fowler and Perez (1999); Perrin et al. (2009); NMFS; Clauset (2013)
Stenella frontalis	133	2.124	Perrin et al. (2009); NMFS; Clauset (2013)
Stenella longirostris	64	1.806	Fowler and Perez (1999); Perrin et al. (2009); NMFS; Clauset (2013)
Steno bredanensis	148	2.170	Fowler and Perez (1999); Perrin et al. (2009); NMFS; Clauset (2013)
Trichechus manatus	1,550	3.190	Fowler and Perez (1999); Perrin et al. (2009)
Tursiops aduncus	200	2.301	Perrin et al. (2009)
Tursiops truncatus	464	2.667	NMFS; Jefferson et al. (1993); Clauset (2013)
Ursus maritimus	388	2.589	Perrin et al. (2009)
Zalophus californianus	238	2.377	Fowler and Perez (1999); NMFS; Aurioles-Gamboa et al. (2015)
Zalophus wollebaeki	109	2.037	Perrin et al. (2009)

Appendix 3

Comparing Humans to Other Species in Regard to Geographic Range Size and Portions of Ecosystems Left Unoccupied

Figure A3.1 shows the data from Table A3.1 regarding geographic range size in relationship to body size (for species common to both Tables A2.1 and A3.1). As can be seen, there is a tendency for geographic ranges of smaller species (roughly similar to humans) to be smaller, on average, than those of larger species ($\bar{x}$ = 21,840,963 vs. 87,643,257 km^2, respectively). This, and the larger variance among smaller species, is similar to what is observed among other taxa, including terrestrial mammals (e.g., Brown and Maurer, 1989; Diniz-Filho and Tôrres, 2002).

Figure 7 (in the main text) is based on calculations of the portion of the Earth's oceans not occupied by the species of marine mammals for which Pompa, et al. (2011) estimated geographic range sizes. These unoccupied areas (areas outside the geographic range of each species) are areas wherein there is no consumption of resources (being mindful of the potential that resources from these areas may migrate, or be carried by currents, to areas within the geographic ranges of the species listed). The unoccupied areas are the equivalent of marine protected areas for each species and are thus informative as empirical examples of holistically sustainable marine protected area.

In the calculations behind the data of Table A3.1, the total area of these oceans was assumed to be 361,900,000 km^2 and the area not occupied by each species was calculated by subtracting the geographic range size of each species. This was then divided by the total area to get the portion left free of the direct influence of consumption (data consonant with the management question involving sustainable portions of the full marine environment to set aside in protected status). Further information regarding the specifics of our methodology can be found in Fowler and Johnson (2015).

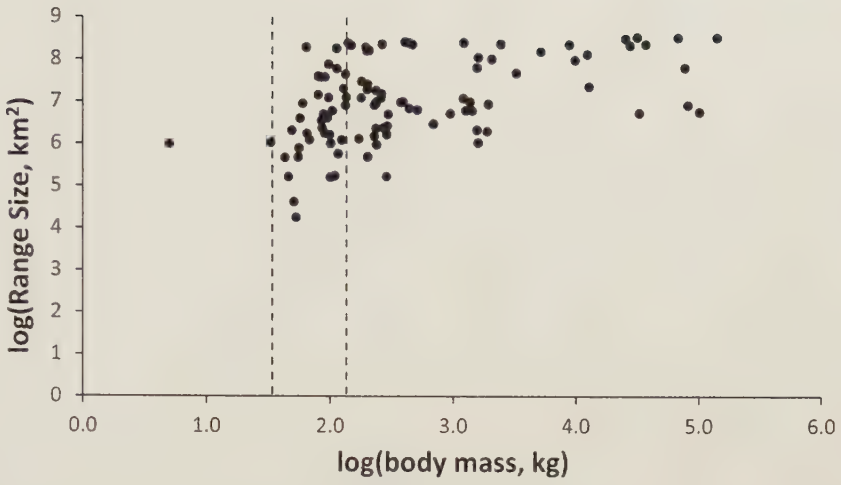

Figure A3.1.—Pattern in geographic range size, as related to body size, for 102 species of marine mammals listed in Table A3.1 for which there are data for body mass (Table A1.1). As in text Figure 1, the dashed lines are the upper and lower bounds of species with body sizes roughly similar to that of humans.

Table A3.1.—Geographic range size for 116 species of marine mammals (from Pompa et al., 2011) showing the percent of the marine environment occupied, and the portion unoccupied, based on 361,900,000 km^2 as a measure of the area of the world's oceans.

Species	Range size (km^2)	% of oceans occupied	Portion of oceans unoccupied
Arctocephalus australis	1,674,290	0.46	0.9954
Arctocephalus forsteri	1,823,240	0.50	0.9950
Arctocephalus galapagoensis	167,512	0.05	0.9995
Arctocephalus gazella	39,155,300	10.82	0.8918
Arctocephalus philippii	163,932	0.05	0.9995
Arctocephalus pusillus	1,705,430	0.47	0.9953
Arctocephalus townsendi	1,045,950	0.29	0.9971
Arctocephalus tropicalis	39,249,100	10.85	0.8915
Balaena mysticetus	8,735,490	2.41	0.9759
Balaenoptera acutorostrata	138,899,000	38.38	0.6162
Balaenoptera bonaerensis	235,109,000	64.97	0.3503
Balaenoptera borealis	325,876,000	90.05	0.0995
Balaenoptera edeni	225,248,000	62.24	0.3776
Balaenoptera musculus	349,620,000	96.61	0.0339
Balaenoptera physalus	348,861,000	96.40	0.0360
Berardius arnuxii	101,075,000	27.93	0.7207
Berardius bairdii	23,620,500	6.53	0.9347
Callorhinus ursinus	12,935,900	3.57	0.9643
Caperea marginata	49,073,400	13.56	0.8644
Cephalorhynchus commersonii	1,780,950	0.49	0.9951
Cephalorhynchus eutropia	493,046	0.14	0.9986
Cephalorhynchus heavisidii	802,273	0.22	0.9978
Cephalorhynchus hectori	42,555	0.01	0.9999
Cystophora cristata	5,167,870	1.43	0.9857
Delphinapterus leucas	10,167,800	2.81	0.9719
Delphinus capensis	9,313,700	2.57	0.9743
Delphinus delphis	31,026,900	8.57	0.9143
Dugong dugon	6,586,460	1.82	0.9818
Enhydra lutris	1,084,750	0.30	0.9970
Erignathus barbatus	12,550,800	3.47	0.9653
Eschrichtius robustus	5,640,160	1.56	0.9844
Eubalaena australis	66,669,400	18.42	0.8158
Eubalaena japonica	5,995,590	1.66	0.9834
Eumetopias jubatus	3,051,310	0.84	0.9916
Feresa attenuata	198,729,000	54.91	0.4509
Globicephala macrorhynchus	238,501,000	65.90	0.3410
Globicephala melas	104,690,000	28.93	0.7107
Grampus griseus	265,158,000	73.27	0.2673
Halichoerus grypus	2,443,290	0.68	0.9932
Histriophoca fasciata	3,625,450	1.00	0.9900
Hydrurga leptonyx	9,900,130	2.74	0.9726
Hyperoodon ampullatus	12,598,000	3.48	0.9652
Hyperoodon planifrons	86,815,900	23.99	0.7601
Indopacetus pacificus	106,594,000	29.45	0.7055
Kogia breviceps	251,271,000	69.43	0.3057
Kogia sima	235,194,000	64.99	0.3501

Table Continued

It is important to note that any area on the surface of the Earth can be taken as an ecosystem. As seen in Figure A3.2, the portion of ecosystems that would be set aside for sustainable protection increases with their size when using the means among species otherwise similar to humans as holistic guidance. As can be seen in Figure A3.3, the portion of the world's oceans used for fishing leaves much less than 93.8% in protected status (the arithmetic mean among species of approximately human body mass, compared to the mean of logit transformed data reported earlier) and additional harvesting to extract mesopelagic biomass would most likely accentuate this abnormality. The portion set aside in marine protected status as a matter of management is miniscule compared to the mean the areas left unoccupied by other species of mammals of our body size).

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Table A3.1.—Continued.

Species	Range size (km^2)	% of oceans occupied	Portion of oceans unoccupied
Lagenodelphis hosei	165,128,000	45.63	0.5437
Lagenorhynchus acutus	8,519,550	2.35	0.9765
Lagenorhynchus albirostris	10,168,600	2.81	0.9719
Lagenorhynchus australis	590,641	0.16	0.9984
Lagenorhynchus cruciger	61,848,200	17.09	0.8291
Lagenorhynchus obliquidens	20,853,700	5.76	0.9424
Lagenorhynchus obscurus	6,186,320	1.71	0.9829
Leptonychotes weddellii	7,146,790	1.97	0.9803
Lissodelphis borealis	12,737,400	3.52	0.9648
Lissodelphis peronii	78,075,800	21.57	0.7843
Lobodon carcinophaga	18,961,100	5.24	0.9476
Lontra felina	996,197	0.28	0.9972
Megaptera novaeangliae	349,580,000	96.60	0.0340
Mesoplodon bidens	13,884,300	3.84	0.9616
Mesoplodon bowdoini	4,419,570	1.22	0.9878
Mesoplodon carlhubbsi	1,096,570	0.30	0.9970
Mesoplodon densirostris	257,754,000	71.22	0.2878
Mesoplodon europaeus	12,338,600	3.41	0.9659
Mesoplodon ginkgodens	3,486,050	0.96	0.9904
Mesoplodon grayi	66,140,000	18.28	0.8172
Mesoplodon hectori	5,066,070	1.40	0.9860
Mesoplodon layardii	83,734,500	23.14	0.7686
Mesoplodon mirus	6,300,090	1.74	0.9826
Mesoplodon perrini	8,015,760	2.21	0.9779
Mesoplodon peruvianus	12,321,700	3.40	0.9660
Mesoplodon stejnegeri	6,809,010	1.88	0.9812
Mirounga angustirostris	2,054,680	0.57	0.9943
Mirounga leonina	8,976,400	2.48	0.9752
Monachus monachus	2,730,360	0.75	0.9925
Monachus schauinslandi	503,740	0.14	0.9986
Monodon monoceros	6,370,340	1.76	0.9824
Neophoca cinerea	1,347,900	0.37	0.9963
Neophocaena phocaenoides	4,086,040	1.13	0.9887
Odobenus rosmarus	5,367,060	1.48	0.9852
Ommatophoca rossii	12,649,700	3.50	0.9650
Orcaella brevirostris	4,252,570	1.18	0.9882
Orcaella heinsohni	1,264,170	0.35	0.9965
Orcinus orca	159,671,000	44.12	0.5588
Otaria flavescens	2,371,930	0.66	0.9934
Pagophilus groenlandicus	8,352,950	2.31	0.9769
Peponocephala electra	167,492,000	46.28	0.5372
Phoca largha	5,173,220	1.43	0.9857
Phoca vitulina	4,233,030	1.17	0.9883
Phocarctos hookeri	171,500	0.05	0.9995
Phocoena dioptrica	2,431,640	0.67	0.9933
Phocoena phocoena	9,201,080	2.54	0.9746
Phocoena sinus	18,196	0.01	0.9999
Phocoena spinipinnis	1,274,860	0.35	0.9965
Phocoenoides dalli	19,888,000	5.50	0.9450
Physeter macrocephalus	239,682,000	66.23	0.3377
Pontoporia blainvillei	480,376	0.13	0.9987
Pseudorca crassidens	115,652,000	31.96	0.6804
Pusa hispida	14,792,000	4.09	0.9591
Sotalia fluviatilis	2,115,420	0.58	0.9942
Sousa chinensis	15,839,700	4.38	0.9562
Sousa teuszii	1,554,490	0.43	0.9957
Stenella attenuata	185,346,000	51.21	0.4879
Stenella clymene	40,843,500	11.29	0.8871
Stenella coeruleoalba	247,740,000	68.46	0.3154
Stenella frontalis	45,684,100	12.62	0.8738
Stenella longirostris	197,320,000	54.52	0.4548
Steno bredanensis	220,032,000	60.80	0.3920
Tasmacetus shepherdi	4,419,310	1.22	0.9878
Trichechus manatus	2,189,720	0.61	0.9939
Tursiops aduncus	26,634,700	7.36	0.9264
Tursiops truncatus	232,786,000	64.32	0.3568
Ursus maritimus	10,273,300	2.84	0.9716
Zalophus californianus	966,957	0.27	0.9973

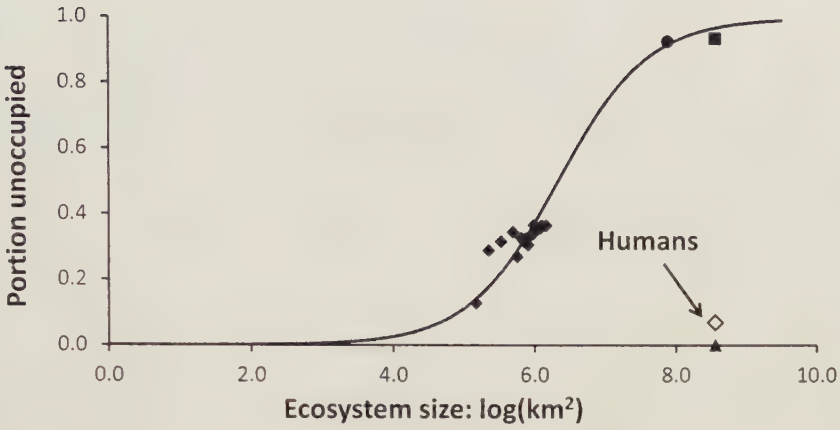

Figure A3.2.—Pattern in mean portion of marine environments left unoccupied by marine mammals, as related to the area being considered. The diamonds to the lower left represent data for 21 species treated by Fowler and Johnson (2015), with the geographic range of each species within the eastern Bering Sea as a distinct ecosystem. The dot to the upper right is for the mean area outside the geographic ranges of the same 21 species expressed as a portion of the entire North Pacific. The square to the upper right represents the mean of unoccupied portions of entire marine environment for species of human body size from Pompa et al. (2011). The symbols at the lower right illustrate the area set aside in protected status by humans (triangle: IUCN: http://www.protectplanetocean.org/collections/introduction/intro-box/globalmpas/introduction-item.html; diamond: Jones et al. (2018)).The curved line assumes upper and lower limits of 1.0 and 0.0.

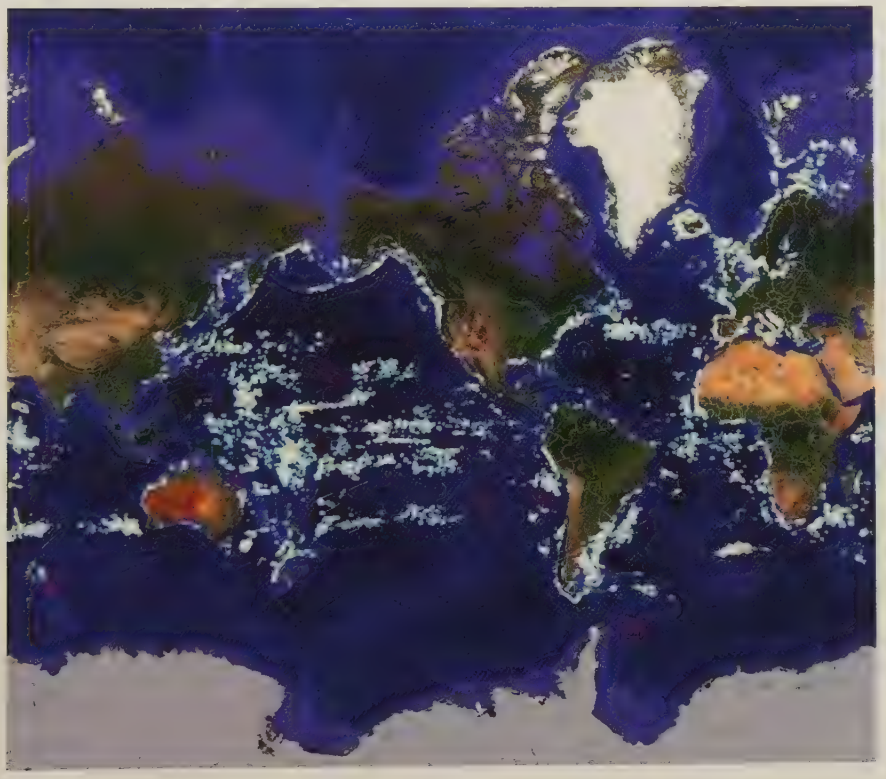

Figure A3.3.—Distribution of fishing activity around the globe from 31 Dec. 2011 to 31 May 2017 based on information displayed at http://globalfishingwatch.org/map/.

The Octocoral Fishery in the Southeastern U.S. and Gulf of Mexico

MARK CHIAPPONE, PAOLA ESPITIA, LEANNE M. RUTTEN, and STEVEN L. MILLER

ABSTRACT—Octocorals, also known as gorgonians and soft corals, were previously managed by the U.S. South Atlantic (SAFMC) and Gulf of Mexico (GMFMC) Fishery Management Councils through a joint Coral Fishery Management Plan (FMP). Because octocorals are mostly collected from Florida waters, the Florida Fish and Wildlife Conservation Commission (FWC) is currently tasked with managing octocoral collection, including the monitoring of colony landings, in the Economic Exclusive Zone (EEZ) adjacent to Florida. Collection of 70,000 colonies per year total, which applies to both state and EEZ waters off Florida, is permitted under Rule 68B-42.006 of the Florida Administrative Code, but has never been exceeded according to available landings data. Before octocoral management responsibility was transferred to the State of Florida, the SAFMC was concerned that octocoral landings data, as opposed to population data, were being used to set Acceptable Biological Catch limits and Overfishing limits under the new Federal fishery management standards. An additional concern with the octocoral fishery and other organisms captured for the marine aquarium and ornamental fisheries is that large taxonomic groups are lumped together, including species with potentially different life histories and ecological functions. This study assessed some of the characteristics of the octocoral fishery by evaluating FWC Trip Ticket data, conducting interviews with octocoral collectors, and analyzing octocoral life history information and available fishery-independent data on population densities and sizes. Based on interviews with collectors, a synthesis of trip ticket results, and population abundance estimates, the long-term stability of the octocoral fishery is not likely to change significantly. The social dynamics of the aquarium industry to seek colorful, rare, and exotic marine species for home aquaria places octocorals at the lower end of the list of desired species. Octocoral distribution and abundance information obtained from an extensive search of the literature, along with available age, growth, and habitat data, suggests that current information is comprehensive and definitive, such that stock assessment or population dynamic modeling could be considered but are probably not required to assess the status of collected octocoral species. For multiple sampling periods, over a decadal period (1999–09) in the Florida Keys, where most octocoral collection occurs, abundance estimates presented for 15 species illustrate that population sizes are large (tens of millions to hundreds of millions of colonies, per species) and abundance is stable or increasing. For example, the numbers of colonies collected in the Florida Keys in two of the collector categories represented < 0.004% of the estimated population sizes. The collectors and aquarium hobbyists interviewed stated that they would welcome and use a field guide to help with octocoral identification, which would ultimately provide better fishery-dependent taxonomic resolution for collected species. The collection of octocorals below the State of Florida quota of 70,000 colonies per year threshold, which has yet to be reached according to landings data, likely does not adversely affect the octocoral populations targeted. This conclusion is based upon the large population estimates determined for octocorals relative to the small number of colonies collected. This conclusion assumes that the distribution and population sizes of targeted species will continue to be relatively stable or increase. Information collected by the State of Florida through trip tickets is probably adequate to understand and manage the octocoral fishery. Minor reporting clarifications and better taxonomic resolution in reporting would help improve the accuracy of collecting data, but improved accuracy is not required to assess the current state of the fishery—the octocoral fishery is sustainable and would likely remain sustainable at colony collection levels orders of magnitude larger.

Introduction

The marine aquarium hobby has witnessed a resurgence in popularity within the United States since the 2007–09 recession (Bricker et al.[1]), with ~1.8 million households owning a saltwater aquarium (American Pet Products Association, 2014). Within the United States, Florida represents the largest component of the ornamental fishery, supplying live marine life to the aquarium industry with over 9 million individual animals per year, encompassing over 600 fish, invertebrate, and plant species (Rhyne et al., 2009). Management of this multispecies fishery is under the authority of the Federal Gulf of Mexico Fishery Management Council, the South Atlantic Fishery Management Council in EEZ waters off North Carolina, South Carolina, and Georgia, and the State of Florida's Fish and Wildlife Conservation Commission (FWC) in Florida. Regulation of the collection of live tropical, ornamental, and marine species in Florida is governed by Rule Chapter 68B-42 of the Florida Administrative Code (FAC). The Florida regulations went into effect in 1991 and have undergone several revisions, affecting bag limits, proper collection techniques, reporting requirements, and area restrictions (and more) for recreational and commercial marine life collectors (Larkin et al., 2001). With a Saltwater Products License, commercial collectors can exceed the daily recreational bag limits that differ by species group. To collect and sell tropical fish and invertebrate species

[1]Bricker J. B., Bucks, A. Kennickell, T. Mach, and K. Moore. 2011. Surveying the aftermath of the storm: changes in family finances from 2007 to 2009. Working paper 2011–17, Mar. 2011, Fed. Reserve Bd., Finance and Econ. Discussion Ser., 38 p. (Online at https://www.federalreserve.gov/pubs/feds/2011/201117/201117pap.pdf).

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such as mollusks, plants, live rock, and live sand, a Restricted Species endorsement and Marine Life endorsement are both required.

The State of Florida has collected commercial landings and effort data since November 1984, maintained in their Marine Fisheries Information System, commonly referred to as "Trip Ticket" data (Larkin et al., 2001). State of Florida landings data on marine life collection date back to 1994. The Florida Marine Life Association (FMLA), the official industry organization for marine life collectors, petitioned the Florida Marine Fisheries Commission in 1988 to adopt standards for the collection of tropical marine life species. Catch regulations were adopted as a result and the collection of marine life and tropical ornamental data were included in the Trip Ticket reporting system beginning in 1994. Originally designed to track the sales of seafood products from Florida waters, the Trip Ticket reporting program requires wholesale dealers to report information about saltwater products purchased (Section 379.362, Florida Statutes, and 68E-5.002, FAC).

Subsequent concerns over the number of new Marine Life (ML) endorsement holders in the industry prompted the FMLA to petition the FWC to limit the entry of new marine life collectors (Division of Marine Fisheries, 2002, cited in Larkin et al., 2001), although an assessment of past and current trends about possible exploitation of individual species had not been conducted (Larkin et al., 2001). As a result, the State of Florida passed Senate Bill 1506 in 1998, which imposed a 4-yr moratorium on the issue of new ML endorsements (Florida Statute 370.06(2)(d)(2)). Further restrictions were introduced in 2005 for those wanting to collect or sell marine life species. In addition to a Saltwater Products License and a Restricted Species endorsement, collectors needed to apply and qualify for a ML endorsement. The endorsements are Marine Life Transferable Dive (MLD), Marine Life Non-transferable Dive (MLN), and Marine Life Bycatch (MLB). To qualify for these endorsements, collectors had to show proof of commercial marine life landings and sales above a $5,000 threshold between the licensing years of 1999 and 2003 (FAC 68B-42.0065). This process eliminated the part-time collectors and brought the number of active ML endorsement holders in the State of Florida down from 743 to 168 (Adams et al., 2001). About 10% of all ML endorsements are currently MLN (M. Bademan, FWC, personal commun.). Collectors wishing to obtain an ML endorsement may now only do so through the transfer of a pre-existing endorsement, since no new endorsements are currently being issued.

Management and Regulation of the Fishery

Octocorals were managed in the U.S. South Atlantic (North Carolina to Florida) and U.S. Gulf of Mexico (Florida to Texas) from 1990–2011 under the joint Gulf of Mexico and South Atlantic Coral Fishery Management Plan (FMP). Restructuring of the Coral FMP in 2011 (Amendment 7) subsequently excluded the management of octocorals in Federal waters off Florida, thereby transferring management responsibility to the State of Florida (FAC 68B-42.009). Octocorals are defined by the State of Florida as "any erect, non-encrusting species of the Subclass Octocorallia, except the species *Gorgonia flabellum* and *G. ventalina*" (FAC 68B-42.002). Recreational collectors may collect up to six octocoral colonies/day with a Florida Recreational Saltwater Fishing License (FAC 68B-42.005). There are no trip or daily collection limits on commercial landings; however, the annual quota for octocorals collected in State of Florida and adjacent Federal waters is currently 70,000 colonies (FAC 68B-42.006). Area restrictions on octocoral collection exist in Atlantic Federal waters north of Cape Canaveral, Biscayne National Park, and in the Stetson-Miami Terrace Deep Water Coral Habitat Area of Particular Concern, as well as the Pourtales-Terrace Deep Water Habitat Area of Particular Concern adjacent to Florida waters (FAC 68B-42.0036).

During collection, no power tools may be used and only one inch of substrate around the perimeter of the base of the octocoral holdfast may be removed (FAC 68B-42.007 and 68B-42.008). Octocorals must be collected alive and stored in a re-circulating live well or oxygenated system aboard the collection vessel (FAC 68B-42.0035). There are additional area closures for marine life collection in southeastern Florida, including National Parks (Everglades, Biscayne, Dry Tortugas), John Pennekamp Coral Reef State Park, and portions of the Florida Keys National Marine Sanctuary, including the Key Largo Management Area (formerly Key Largo National Marine Sanctuary), the Looe Key Management Area (formerly Looe Key National Marine Sanctuary), and various smaller no-take zones including Sanctuary Preservation Areas, Special-Use/Research-Only Areas, and Ecological Reserves (15 CFR 922 Subpart P).

Collector and Fishery Characteristics

Collector Demographics

Of the 168 ML tiered endorsement holders in Florida in 2013, only 64 reported octocorals landings.[2] After consulting two marine life collectors familiar with the fishery, 53 octocoral collectors were identified as active collectors based in the Florida Keys (n=30 collectors), the Florida east coast (n=14), and the Florida west coast (n=9). A letter that described the goals of this study with a request for additional information about the octocoral fishery was sent to the 53 active collectors. A second (and in some cases a third) request for information was sent via email to collectors (n=30). Telephone and in-person interviews were conducted with 15 collectors, including 8 from the Florida Keys, 5 from the Florida east coast, and 2 from

[2]Florida Fish and Wildlife Conservation Commission, Tallahasse, Florida. Unpubl. data, Nov. 2014.

the Florida west coast. Interview questions addressed the fishery (i.e., species collected, colony size, collection sites, and collection frequency), collection methods (i.e., collection techniques, holding facility set-up, and shipping logistics), and social issues within the fishery (i.e., purpose for starting a business, amount of time spent collecting, and collector etiquette). Information gathered from interviews and field visits to the Florida Keys (5 collectors visited) and Miami (2 collectors visited) was used to summarize octocoral fishermen and fishery characteristics.

In the State of Florida, octocoral collectors are required to hold a Saltwater Products License, Restricted Species endorsement, and a ML tiered endorsement (MLD, MLN, or MLB). These endorsements were either purchased before the moratorium on the issue of new ML endorsements in 2005, or they were purchased from an existing license holder, typically as a package including the entire business (e.g., boat, warehouse, holding tanks, and collection sites). This is an expensive purchase considering the cost (~$35,000 US) of the ML endorsement.[3] Many (n=11) of the collectors interviewed are lifelong ocean and aquarium enthusiasts who have been diving since the 1960s and 1970s; thus, they have extensive experience to know where to efficiently find their target organisms. Other collectors (n=4) learned the trade through an apprenticeship of sorts, helping a current ML holder while learning proper collection techniques. Over half (58%) of the octocoral collectors contacted live in the Florida Keys (Monroe County), with the remaining residing on either the Florida east coast (22%) or west coast (20%). While octocorals are collected throughout Florida waters, 80% of reported landings come from Atlantic waters[2], with the majority of the collection effort focused on Florida Keys shallow-water species.

[3]Anonymous marine life collectors interviewed in southeastern Florida, Personal commun., 2013–14.

Table 1.—Octocorals typically collected in the Atlantic Ocean off Florida (H. Feddern, personal communication).

Species group	Scientific name	Collector common name
Other	*Diodogorgia nodulifera*	yellow finger/colorful sea rod gorgonian
	Eunicea sp.	brown tree gorgonian
	Muricea sp.	silver gorgonian
	Plexaurella nutans	large polyp gorgonian
	Pterogorgia citrina	yellow ribbon gorgonian
Purple	*Antillogorgia* sp.	purple plume gorgonian
	Antillogorgia sp.	purple willow gorgonian
	Antillogorgia elisabethae	purple frilly gorgonian
	Muriceopsis flavida	purple brush gorgonian
	Pterogorgia anceps	purple ribbon gorgonian
Red	*Diodogorgia nodulifera*	red finger gorgonian
	Swiftia exserta	orange tree gorgonian

Octocorals are mainly collected for the aquarium trade and not for the curio trade. A few opportunistic ML endorsement holders hold a MLB endorsement, which allows them to keep whole octocorals that are incidentally caught by shrimp nets. Since the quality of specimens obtained from bycatch is typically not suitable for the marine life trade due to tissue damage and broken branches, such colonies are dried and sold for the curio trade.[3] Because shallow-water octocorals are found in great abundance throughout hard-bottom and coral reef habitats of south Florida, these fauna are typically easy to find and can be collected year-round. In contrast, because deeper water (> 30 m depth) species such as *Diodogorgia nodulifera*, *Swiftia exserta*, and *Leptogorgia* spp. are more challenging to collect because of strong currents and the constraints of deeper diving, only a few of the collectors interviewed target deeper water (> 30 m) species.

Despite the general ease in finding octocorals, no ML endorsement holders collect and sell octocorals exclusively. In a few cases (n=3), octocorals represent nearly 50% of total marine life sales for collectors; however, more commonly (n=12) octocorals comprise 20% or less of total marine life sales. The fishery is demand-driven, which means that octocorals are primarily collected upon request from wholesalers, retail stores, public aquariums, and aquarium hobbyists. The demand for octocorals within the aquarium industry has never been sufficient to support a business focused exclusively on octocoral collection. As a result, marine life collectors spread their efforts across collecting and selling marine fishes and a variety of invertebrates such as crabs, corallimorpharians, anemones, and snails. Table 1 lists the octocorals commonly collected for the aquarium trade in Florida (Feddern[4]) and Table 2 is an expanded list of species that was provided by marine life collectors interviewed and by FWC.

Collection Methods

Aquarium owners generally prefer clean, brightly colored purple, red, or yellow octocoral specimens that are heavily branched with large polyps in good condition (e.g., no visible signs of tissue loss or bleaching). Size matters, with specimens usually small enough to fit comfortably in home aquariums (< 20 cm in height). Octocorals are collected using snorkeling, SCUBA, or hookah diving rigs. A hammer and chisel or dive knife is typically used to remove whole colonies (Fig. 1). As per FAC 68B-42.007, the holdfast and substrate with a maximum diameter 1-in or less can be removed along with the colony. Some of the collectors interviewed believe that preserving the substrate with the holdfast increases the survivorship of a colony, but no formal studies have been conducted to test this observation.

Octocorals collected off the west coast of Florida, such as *Leptogorgia* spp., are often removed by hand from nearshore artificial reefs and bridge

[4]Feddern, Henry. Marine life collector, Florida Keys. Personal commun., Oct., 2013.

Figure 1.—Octocoral collector, Dr. H. Feddern, using a hammer and chisel to remove octocoral colonies to be sold in the aquarium trade.

Table 2.—Octocorals collected in the Atlantic Ocean and the Gulf of Mexico off Florida based upon personal communications with Florida collectors during 2013–14. Asterisk (*) indicate the most highly demanded octocoral taxa.

Species group	Scientific name	Collector common name(s)	Collection location
Other	*Antillogorgia acerosa*	golden plume gorgonian	Atlantic
	*Diodogorgia nodulifera**	yellow finger/colorful sea rod gorgonian	Atlantic
	Muricea sp.*	delicate spiny sea rod	Atlantic
	Muricea elongata	orange spiny sea rod/rusty gorgonian	Atlantic
	Muricea muricata	spiny sea fan	Atlantic
	Muricea pinnata	long spiny sea fan/silver gorgonian	Atlantic
	Plexaura homomalla	black sea rod	Atlantic
	Plexaurella fusifera	brown tree gorgonian	Atlantic
	*Plexaurella nutans**	giant slit pore/large polyp gorgonian	Atlantic
	*Pterogorgia citrina**	yellow ribbon/yellow sea whip gorgonian	Atlantic
Purple	*Antillogorgia* spp.	purple frilly/purple whip gorgonian	Atlantic, Gulf
	*Antillogorgia acerosa**	Purple or golden willow gorgonian	Atlantic
	*Antillogorgia elisabethae**	purple frilly gorgonian	Atlantic
	*Antillogorgia kallos**	purple plume/bi-pinnate gorgonian	Atlantic
	*Briareum asbestinum**	corky sea finger/sea stalk gorgonian	Atlantic
	Eunicea spp.	purple knobby/knobby sea rod/warty sea rod gorgonian	Atlantic
	*Eunicea flexuosa**	purple candelabra/swollen knob candelabrum gorgonian	Atlantic
	*Muriceopsis flavida**	purple brush/bottle brush gorgonian	Atlantic
	Pseudoplexaura sp.	porous sea rod	Atlantic
	Pseudoplexaura porosa	purple tree gorgonian	Atlantic
	*Pterogorgia anceps**	purple ribbon/angular sea whip gorgonian	Atlantic, Gulf
	Pterogorgia guadalupensis	purple blade/flat-blade/grooved-blade sea whip gorgonian	Gulf
Red	*Diodogorgia nodulifera**	red finger/colorful sea rod gorgonian	Atlantic
	Ellisella barbadensis	Devil's sea whip	Atlantic
	Icilliogorgia schrammi	orange deep-water fan	Atlantic
	Leptogorgia punicea	sea whip/carmine sea spray gorgonian	Atlantic, Gulf
	Leptogorgia virgulata	sea whip gorgonian	Gulf
	Nicella schmitti	red/bushy sea whip	Atlantic
	*Swiftia exserta**	orange tree/red polyp gorgonian	Atlantic

pilings. This is similar in the Florida Keys; however, both locations also involve substantial collection directly from the natural seabed. Collected colonies are placed in mesh bags or plastic collection containers during the dive, and then stored in covered species-specific live wells or 5-gallon buckets with air stones during transport to a holding facility. Water changes are done throughout the day (P. Espitia, personal observ.). Collectors usually fulfill octocoral orders within an hour, so the remainder of the day is spent collecting other marine species. Collectors with wholesale orders noted that they collect as many as 600 octocorals per month, and then distribute several large orders to wholesalers. Collection sites are species-specific and several types of marine life (e.g., emerald crabs, *Mithraculus sculptus*) may be targeted along with octocorals at a single site. All of the collectors interviewed specified that they have multiple sites from which colonies are removed and that they are conscious to rotate sites to reduce collecting stress on individual site locations. Although collectors do not officially share their work site locations with each other, they generally avoid one another. Some Florida Keys marine life collectors noted that in the past they were followed by other collectors who would try and learn where they were collecting, especially where cryptic or prized specimens that are worth more money were located.

The octocoral collectors interviewed stated they are cautious about storage methods, because negative interactions between species can occur. For example, the slimy sea plume, *Antillogorgia Americana*, is not sold in the aquarium trade because the excess slime it produces fouls the water during storage and shipment, killing other octocorals within the same aquarium system. Other "sea plumes" (*Antillogorgia* spp.) reportedly are caustic to other octocoral genera. The high concentration of prostaglandins in *Plexaura homomalla* (Bundy, 1985) causes caustic reactions when stored with other octocorals, even individu-

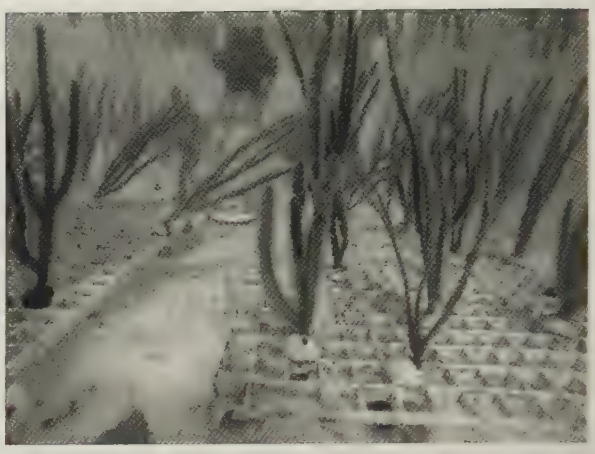


Figure 3.—Eco-Gorgs® are kept upright in flat plastic egg crates within a greenhouse holding facility in the Florida Keys.

Figure 2.—(Greenhouse style octocoral holding facility in the Florida Keys.

als from the same species. One collector reported that some morphologies of *Eunicea flexuosa* will "burn" the tissue of other octocorals, causing it to slough off. *Plexaurella* species and some deepwater species such as *Ellisella barbadensis*, *Nicella schmitti*, and *Swiftia exserta* are reportedly sensitive to physical damage and to allelochemical interactions with other species, so collectors keep these fauna in individual bags during collection and storage. Collectors who sell the deepwater octocoral *Diodogorgia nodulifera,* on the other hand, described this species as hardy and indicated that colonies can be housed in close proximity with conspecifics and *S. exserta.* While none of this information is proprietary, collectors have learned by trial and error how to best collect and store octocorals to maximize profit by minimizing the number of specimens collected and maximizing their survival after collection. This contrasts, for example, with the way that some marine ornamental species, particularly fishes, are collected internationally such as in the Philippines, where large numbers are collected from reefs and only a few survive to be sold to consumers (Wood, 2001).

Collected octocorals are usually housed in long raceway aquaculture tanks (~4.6 m x 0.6 m x 0.6 m) located in greenhouses or warehouses (Fig. 2). Two of the facilities visited have direct access to bay or inlet waters and had a flow-through water filtration system. Other operations mix their own saltwater (n=12) or have it trucked in (n=1), and then ship octocorals in treated water. Octocoral colonies with slender branches, such as sea plumes, are stored upright with their holdfasts buried in a bed of sand or fine gravel substrate, while those with more robust branches (e.g., *Eunicea* and *Pseudoplexaura* species) are suspended upside-down with their holdfasts secured within a piece of foam (similar to a pool noodle). Fragmented colonies can be stored upright with their plugs secured within sheets of plastic egg crates (Fig. 3).

The length of time octocorals are held within a warehouse facility before being shipped ranges from several hours to several weeks. Some collectors wrap wet paper towels or newspaper around individual colonies, and then place six wrapped colonies in a plastic bag with a small amount of wa-

Figure 4.—Branch fragments being clipped from a *Eunicea flexuosa* colony to be sold as Eco-Gorgs®.

Figure 5.—*Eunicea flexuosa* fragment is super-glued into a concrete plug to be sold as an Eco-Gorg®.

ter. Wrapping the colonies keeps them moist and self-contained, which helps to minimize contact with other colonies if they start to deteriorate during shipping. For high-volume shipments of 100 or more colonies, this technique is too labor intensive. Some collectors have had inconsistent results with wet paper towels, so they instead pack individual colonies in small plastic bags and inject hospital-grade oxygen along with a small amount of water to keep the colonies wet. Another method used is to place only the holdfast in water and then hand-vacuum-seal the bag; however, many collectors noted that air exposure kills the colonies. Depending on the species, a dozen or so colonies can be placed in a single bag (e.g., *D. nodulifera* and *Leptogorgia* spp.), while other octocorals must be packed individually (e.g., *P. homomalla*). To minimize costs associated with colony holding and shipping, one collector transfers his collection from the vessel to live wells in the back of a truck, and then delivers the octocorals directly to wholesalers, which keeps the process simple and lowers costs.

A growing number of collectors are adopting the Eco-Gorg®[5] technique, in existence since at least the early 1990s, to reduce potential collecting impacts on colonies and populations. The Eco-Gorg® technique involves clipping branch tips ~10-cm in length from larger established colonies (Fig. 4), instead of removing entire colonies from the seabed. From 1 to 20 branch tips per colony are removed and after the colony base of each clipping is stripped of its tissue, they are inserted into concrete plugs and super-glued into place (Fig. 5). The clippings are kept in holding tanks for a few weeks to allow tissue to grow over the concrete plug. The collectors interviewed stated that if they keep octocorals longer in their holding facility, then the colonies acclimate better to an aquarium environment, thus making them hardier for customers. Species fragmented and marketed as Eco-Gorgs® include *Antillogorgia acerosa, Briareum asbestinum, Eunicea calyculata, E. flexuosa, E. succinea, Muricea elongata, Plexaura homomalla,* and *Pterogorgia guadalupensis.* One deepwater collector interviewed uses this technique to collect *Swiftia exserta* more quickly and efficiently in challenging high current, deep-diving conditions. *S. exserta* is collected in Palm Beach County along the edges of the southeast Florida reef tract from 18–46 m depth, where high densities of large colonies are intermixed with *Diodogorgia nodulifera* and *M. elongata.* Colonies tend to be short and rigid in high-current environments. One collector interviewed also finds these deeper water taxa in Miami-Dade County at 27 m depth; however, densities are lower and colonies are taller and more flexible at these sites. Between five and ten branch clippings, 20-cm long, are removed from colonies over one meter in height. As many as 70 clippings can be collected in ten minutes. Not all octocorals can be collected using the Eco-Gorg® technique. *D. nodulifera* colonies, for example, lack a proteinaceous central axis and

[5]Mention of trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

thus cannot be adhered to a plug or other substrate for growing out in a holding facility.

Aquarium hobbyists generally desire fragmented colonies for several reasons. First, they are a sustainable alternative to removing whole colonies from the reef. In addition, they offer the potential to introduce more variety to aquariums because specimens that may otherwise be too large can be made available as smaller colonies. The fragments also tend to be hardier, since they have already survived storage in the artificial systems maintained by the collectors or wholesalers. Aquarium hobbyists also state that Eco-Gorg® fragments are easy to establish in their aquariums because they are already accustomed to receiving fragments of stony corals and corallimorpharians attached to plugs. Marine life vendors have begun to adopt the fragmentation process and on occasion request large whole colonies that they clip themselves and then sell as fragments.

Economics of the Fishery

Octocoral collectors sell to wholesalers, retail stores, hobbyists, and public aquariums both domestically and internationally. One interviewed collector, for example, supplies octocorals primarily to public aquariums, but also sells to wholesalers in China and Japan and a few domestic pet stores. Wholesale dealers and retail stores work closely with one another, so marine life collectors are careful not to undercut wholesalers by dealing directly with retail stores.

Collectors who sell directly to hobbyists are typically working with a "purist" market—where buyers are trying to recreate a reef ecosystem in their home aquaria. Buyers looking for high-quality Caribbean species that are sold at reasonable prices hear about these direct-sale-collectors by word-of-mouth. This results in a steady demand for octocorals that is additionally driven by social media outlets and marine aquarium forums such as ReefBuilders (reefbuilders.com), Reef Central (reefcentral.com), and Coral Magazine (coralmagazine.com). Such networks have contributed greatly to the expanding knowledge base of octocoral care and sales.

The international market for Caribbean octocorals exists because international hobbyists seek out exotic, seemingly rare species to keep in their home aquariums. The collectors interviewed stated that they ship octocoral colonies to Canada, Israel, Ukraine, and Asia, with several also shipping to the European Union despite needing a health certificate from the U.S. Department of Agriculture, along with veterinarian inspections of collection stocks and holding facilities. Germany in particular has become a leading manufacturer of aquariums and aquarium products that serve a popular reef-keeping hobby. When the Cold War political divisions blocked access to aquarium resources, aquarists in East Germany were forced to dedicate their husbandry efforts to a limited number of species, mainly soft corals from the Mediterranean Sea, and to construct their own filtration systems. The reunification of Germany gave rise to greater access to tropical marine animals; however, the popularity of reef-centric aquariums remained and now many home aquariums in Germany are dominated by invertebrates, especially octocorals (Luty, 2014).

The mark-up rate from collector to retailer is approximately 10-fold, with retailers purchasing colonies from collectors for $2 to $5 per colony and then selling those colonies for $20 to $50 each. Working with wholesalers tends to bring reduced prices per colony for the collector; however, collectors can sell 100 colonies at a time rather than just 5–15 colonies. In addition, once a relationship is established between a collector and a wholesaler, wholesalers show loyalty to their collectors and will subsequently purchase from them despite competitors offering lower prices. Collectors do have influence over their distribution and prices, especially when healthy specimens are difficult to find or if collecting conditions such as inclement weather make collecting challenging. The extensive warm temperatures in south Florida in 2014 resulted in massive bleaching of a number of octocoral species including *Antillogorgia* spp., *B. asbestinum*, *Muricea* sp., and *Plexaurella* spp. In addition, elevated concentrations of the marine dinoflagellate *Karenia brevis* created an algal bloom off the west coast of Florida[6], killing a substantial number of octocorals as stated by one collector. In such cases, collectors must travel further distances to find suitable specimens to collect, resulting in price increases to offset extra fuel costs. Deepwater octocoral collectors have an apparent competitive advantage over shallow-water collectors because demand for their specimens is relatively high, due to the vibrant coloration (red, orange, and yellow) of the deepwater colonies. Collectors also work to emphasize the "special" nature of deepwater octocorals by partially filling orders, or only collecting these species every couple of months. Intentional or not, the perception remains that deepwater octocorals are "special," so this places a higher value on colonies (Anonymous collector, personal commun.). However, deepwater octocorals are also more difficult to maintain in good condition in aquaria, reducing demand.

Internal costs associated with collecting marine life organisms are high and include operational costs, maintenance costs, and other associated costs (Table 3). Per week, the collectors interviewed stated that they could spend $400 on collection trips. For this reason, octocoral collectors sometimes work with other marine life collectors to fill gaps in their own supplies. Other costs include annual renewal fees such as the $550 fee for a Wholesale Dealer License. Unforeseen costs include fines from FWC; for example, for not using an air stone or recirculating live well to keep octocorals in a healthy condition, or the revocation of an ML license for failure to report Trip Ticket data (e.g., loss of the purchase

[6]FWC. 2014. Red tide current status, accessed 14 Dec. 2014 at https://myfwc.com/research/redtide/statewide/.

Table 3.—Costs associated with owning a marine life collection business according to interviewed octocoral collectors in Florida.

Costs
Operational
Fuel (personal vehicles)
Fuel (boat)
Warehouse facility rental/mortgage
Aquarium system setup
Electricity
Staff/crew, food, ice
Maintenance
SCUBA gear
SCUBA tank fills
Boat
Aquarium products (water, salt, etc.)
Packing and shipping supplies
Associated
License/endorsement renewal
Insurance (personal vehicle)
Insurance (boat)
Insurance (facility)
International shipping fees

Table 4.—Annual landings, number of collection trips, average price per colony, and estimated value of octocorals in State and Federal waters in Florida, 1994–2012, based upon commercial marine life trip ticket data (FWC, 2014).

Year	No. collected	Total trips	Average price/colony ($)	Estimated value ($)
1994	32,106	764	3.80	121,983
1995	35,976	889	2.42	87,186
1996	37,057	702	2.80	103,739
1997	44,867	725	2.34	104,866
1998	40,743	832	2.23	91,029
1999	36,621	790	2.23	81,662
2000	43,100	997	2.50	107,914
2001	45,894	956	2.60	119,304
2002	38,138	880	2.51	95,731
2003	44,484	926	2.63	117,140
2004	43,708	1,018	2.74	119,802
2005	41,452	905	2.88	119,515
2006	48,567	1,004	2.96	143,538
2007	44,273	864	3.29	145,759
2008	42,642	826	3.57	152,029
2009	42,481	784	2.93	124,533
2010	32,237	695	4.08	131,529
2011	28,942	701	3.52	101,780
2012	33,228	625	3.85	127,839

price and sales associated with the ML license).

Challenges in the Octocoral Fishery

The biggest challenge faced by octocoral collectors is the relatively low demand for colonies by aquarium hobbyists, as well as finding and retaining customers. Maintaining live octocorals in aquaria is also a difficult and relatively costly hobby, compared to maintaining only fishes. In addition, there are substantial physical challenges inherent when diving and collecting marine life. Long days spent on the water mean exposure to the elements, venomous marine life such as lionfish, *Pterois* spp., and jellies, and physical fatigue. Marine life collection can also require diving expertise, especially when diving in strong currents and deeper water. Palm Beach County is notorious for its high-current regime due to the proximity of the Gulf Stream to the coast, so collectors prefer to drift dive with their boat. Many collectors operate alone while diving because they feel safer not having to keep track of a dive buddy. Limited market potential and difficulty collecting combine to make octocoral collecting a niche business, usually a small part of a larger enterprise that involves collecting a diversity of marine organisms.

Adverse environmental conditions, such as temperature-related bleaching events and algal blooms, can weaken and cause octocoral mortality, making it difficult to find viable specimens to sell. Even healthy colonies can quickly deteriorate and become unviable if they are not handled or stored properly. In addition, maintaining octocoral colony health in an aquarium system is challenging because octocorals require adequate spacing among colonies, water quality, appropriate lighting (e.g., lower light output for deeper water octocorals), and relatively strong water flow. Deepwater species also require a supplemental food source since they lack symbiotic microalgae (zooxanthellae). Aquarium system construction and maintenance is also expensive. Some collectors who do not live near a clean source of saltwater have to pay for saltwater transported to their warehouses.

Economically, the octocoral industry supplies the larger aquarium trade, which is itself a luxury hobby, especially as related to keeping live corals and octocorals. Price fluctuations and octocoral supply problems are largely uncontrollable by collectors. For example, when healthy octocoral colonies become scarce due to bleaching, algal blooms, or other factors related to environmental stress, collectors must travel further distances to find viable colonies, which, in turn, raises the price of octocoral colonies. Hobbyists are usually unaware of the causes of price increases, so they often turn to less expensive sources or alternative species from international markets. For instance, a collector interviewed from the Florida Keys who was mining natural live rock in the 1980s stated that once the State of Florida prohibited live rock collecting in State waters in 1992 (FAC 68B-42.008), marine aquarium hobbyists shifted their attention to Haiti to acquire inexpensive Caribbean live rock. During economic downturns, such as the recession of 2008, the price per octocoral colony declined (Table 4) because of less disposable income to spend on luxury aquarium items, which, in turn, placed pressure on collectors' daily maintenance and operation costs (Table 3). Coupled with the relatively low demand for octocorals (historically and presently), collectors typically rely on other marine life species to increase profits. During the past 20 years in Florida, snails, crabs, starfish, shrimps, and anemones constituted the most popular aquarium invertebrates sold to the aquarium trade (Table 5).

Future of the Fishery

The state of the octocoral fishery has remained relatively stable since 1994 (FWC, 2014). In the last six years, however, there has been a decline in demand of octocorals by aquarium hobbyists (Table 4). The marine aquarium hobby is susceptible to trends, much like the fashion industry

Table 5.—Annual landings and economic value of marine invertebrate species groups collected in Florida, 1994–2012, based on commercial trip ticket data (FWC, 2014).

Invertebrate group	Annual landings		Change in landings, 1994–2012 (%)	Value ($)		Change in value 1994–2012 (%)
	1994	2012		1994	2012	
Snails	290,211	3,308,614	1,040	173,812	449,102	158
Crabs	117,889	2,667,574	2,163	100,617	543,191	440
Sand Dollars	643,105	1,484,091	131	64,631	143,110	121
Shrimp	33,719	1,754,445	5,103	32,374	353,760	993
Starfish	314,071	25,414	-92	298,922	40,705	-86
Anemones	307,891	65,626	-79	164,671	136,621	-17
Octocorals	32,106	33,228	3	121,983	127,839	5

changing styles from year-to-year. One of the most popular current trends is related to aquarium lighting. Advances in lighting technology have replaced large, heat-producing, energy-draining lights with more compact, energy-efficient LED lights that provide focused light into reef tanks (Joshi, 2010). Actinic lights have also become popular in reef aquariums because they highlight the fluorescence within coral polyps. As a result, saltwater aquariums are no longer dominated by just fishes, but by other colorful species such as corallimorpharians and zoanthids. Since most octocorals apparently do not fluoresce under such lighting conditions, they are not currently part of this trend.

Aquarium hobbyists also seek shortcuts in reducing the time it takes to perform maintenance duties on home aquaria, such as siphoning out excess food and detritus or removing algae. As a result, "cleaner" invertebrates such as snails and crabs are now common elements in aquariums. Because marine hobbyists often spend a lot of time, effort, and money, they enjoy sharing and showing off their aquaria. Several marine aquarium forums have "tank of the month" pages (e.g., www.reefcentral.com, Reefkeeping Magazine, and Ultimate Reef) that encourage hobbyists to send in photographs of their home aquariums for others to learn from or to reserve "bragging rights" for a job well done. Part of this social dynamic is seen in the variety of species within these tanks. Exotic and rare species such as the peppermint angelfish, *Centropyge boylei*, a deepwater angelfish known to only inhabit the Cook Islands, are highly sought after, despite the $20,000 retail value (Ho, 2011). Since octocorals are not considered rare or exotic (at least in the U.S.), they are not currently part of this trend.

What would need to occur for the octocoral fishery to boom in Florida or the greater southeastern U.S. and Gulf of Mexico? The only real boom in octocoral collection—and it was small—occurred in the mid-1990s after culture techniques were developed that were relatively easy for home aquarium hobbyists to adopt. During this period, octocorals became associated with keeping seahorses in aquariums, which elevated octocoral demand slightly. On a limited scale, the encrusting octocoral *Erythropodium caribaeorum* was once collected for a unique secondary metabolite that had pharmaceutical properties. The biocompound, however, was synthesized quickly by a Canadian company, subsequently resulting in reduced demand for this species (Taglialatela-Scafati et al., 2002). The only other actively collected octocoral for the pharmaceutical industry presently, at least that we are aware of, is *Antillogorgia elisabethae*, which is collected in the Bahamas and perhaps elsewhere (Castanaro and Lasker, 2003). Typically, when a bioactive compound is isolated from a marine species with potential for commercial application, considerable effort is expended to synthesize the compound in the laboratory, since collection from natural populations rarely provides a reliable or sustainable source of the bioactive material. It is possible that an octocoral species could suddenly become fashionable and result in increased demand. For example, EcoGorgs® were first introduced in the late 1990s, and then declined in popularity. Demand then increased when they were re-introduced due to demand for apparently sustainable and ecologically friendly products. Working against the trade is the fact that the most colorful species are typically the most difficult to collect, as they are usually the deeper water species found in high-current regimes. Such fauna are also more difficult to maintain in good condition in hobbyist aquariums. In the mid-1990s, for example, "red" octocorals were marketed at a higher price point because they were clearly attractive as ornamentals, but demand could not be sustained.

The octocoral collectors interviewed have a positive outlook on the future of the octocoral fishery, yet are realistic when discussing the future. Collectors have experienced trends that fluctuate with the vagaries of the aquarium trade, yet they have adhered to collecting and selling octocorals typically because there are reliable buyers who provide a relatively small but steady income. A few of the collectors interviewed spoke optimistically about the potential for growth as hobbyists begin to learn more about octocoral husbandry requirements through aquarium hobby online forums. Technological developments in power heads that simulate wave-driven water movement may also facilitate octocoral husbandry. Collectors are adept at the use of social media outlets to market their marine organisms. Formal, potentially costly, marketing approaches have not apparently been attempted based upon the responses from the collectors interviewed. Some collectors lamented the difficulty in finding reliable customers who keep octocorals in their aquaria, noting flat sales over the years, compared with sales of other invertebrate organisms such as crabs and corallimorpharians. Many collectors interviewed mentioned that they would welcome a concerted effort on the part of the scientific community to validate the sustainability of octocoral collection, which they think might help promote interest and boost sales. Indeed, that is one reason why so many collectors were willing to be interviewed for this study.

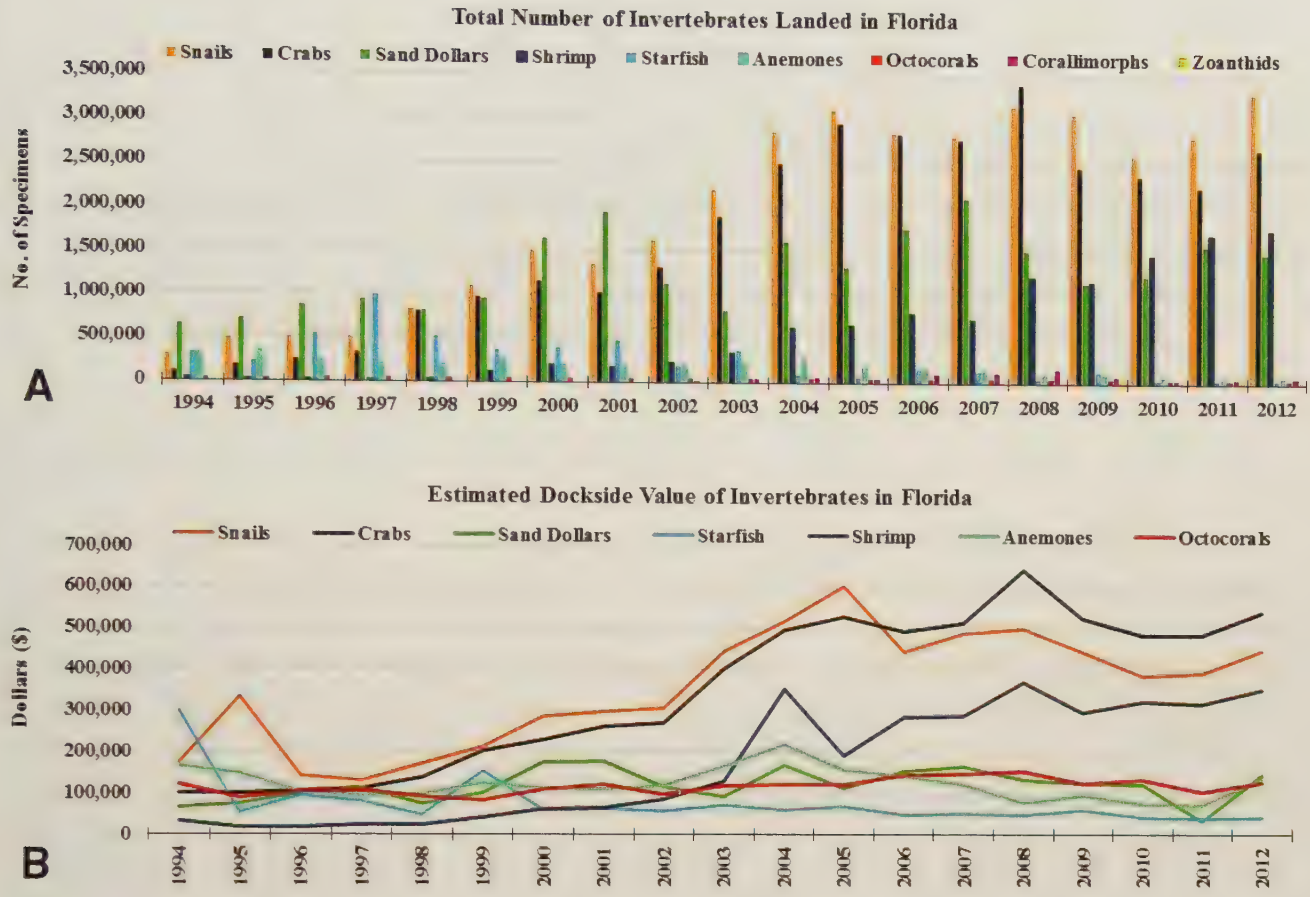


Figure 6.—(A) Annual landings and (B) dockside value of invertebrates for the marine aquarium trade in Florida, 1994–2012 (FWC, 2014).

Commercial Marine Life Landings and Values

Invertebrates

A principal driver of the marine life fishery in the U.S. South Atlantic and Gulf of Mexico is that it is a demand-based fishery for aquarium hobbyists and for the curio trade. Historically, the marine aquarium trade has been fish-centric; however, developing technologies in lighting and filtration have advanced the husbandry of invertebrate species, thereby opening the hobby to greater demand for other reef organisms (Rhyne and Tlusty, 2012). For example, during 1990-98, invertebrate landings accounted for an average of 63% of the total value of annual dockside landings within the Florida marine life fishery (Adams et al., 2001). During this same period, octocorals represented only 4.4% of all invertebrates collected (Larkin et al., 2001). Instead, gastropod snails, crabs, sand dollars, shrimps, starfish, and anemones represented the top invertebrate groups collected (Fig. 6A). Since the State of Florida FWC began keeping public records of commercial landings in 1994, declines in landings of starfish and anemones have given rise to dramatic increases in the collection of shrimps, crabs, and snails on an annualized basis (Fig. 6A, Table 5). The increased demand for organisms that graze algae and scavenge detritus reflects demand by hobbyists for organisms that provide an aquarium service (i.e., control and removal of algal growth and detritus) for their home aquaria (Rhyne et al., 2009). Sand dollars are collected for the curio trade and experienced a 57% increase in collection levels since 1994 (FWC, 2014). As demand increases for such organisms, so too does their dockside value. The dockside value of ornamental cleaner shrimp, for example, increased by 52% on an average annualized basis from $32,374 in 1994 to $353,760 in 2012. Crab, snail, and sand dollar values exhibited similar increases in value (Fig. 6B, Table 5).

Octocorals

Octocorals are valued because at least some specimens provide aesthetic beauty to home aquaria. However, because most octocorals lack the color vibrancy of other invertebrates, they have not experienced the same collection intensity as other marine life

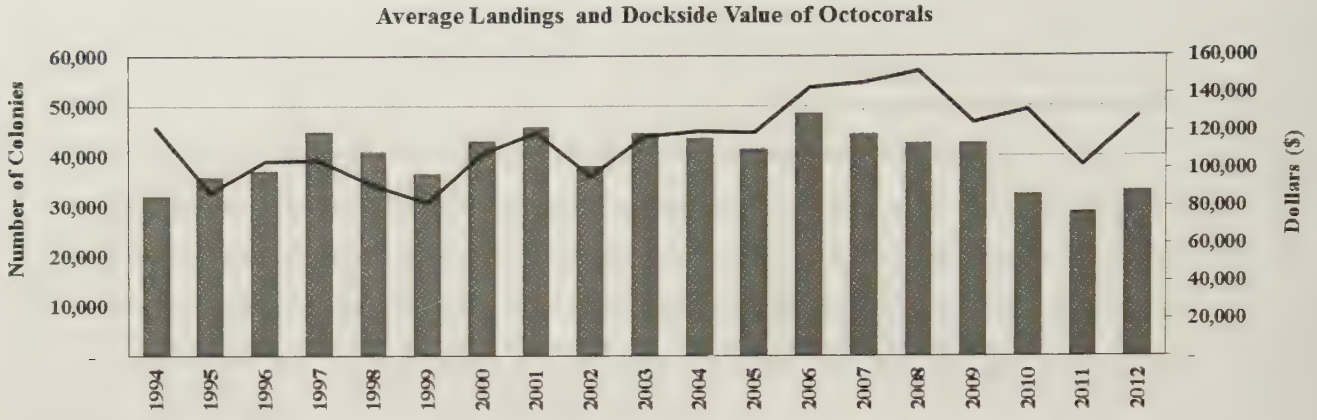


Figure 7. –Average annual landings (bars) and dockside value (line) of octocorals collected in Florida, 1994–2012 (FWC, 2014).

organisms. Since 1990, the FWC has collected annual landings data that includes the number of octocoral colonies landed; however, landings are not partitioned by taxonomic classification but instead by color categories (FAC 68B-42.001). According to the FAC (Rule 68B-42), the term "octocoral," which also includes "soft coral," means "any erect, non-encrusting species of the subclass Octocorallia, except the species *Gorgonia flabellum* and *Gorgonia ventalina*." FWC also collects commercial octocoral fishery data pertaining to the number of collection trips made, average price per colony, and average dockside value of octocorals using trip ticket reports. As reflected in nearly 20 years of available commercial trip ticket data, octocoral annual landings increased by only 3%, while the price per colony has nearly doubled, from $2.23 in the late 1990s to $4.08 in 2010 (Fig. 7, Table 4). Noteworthy is that the price per specimen is considerably higher than for many other invertebrate groups, which generally sell for less than $1.00 per specimen. In 2006, the octocoral fishery experienced a surge in hobbyist demand, resulting in 48,567 colonies collected during 1,004 commercial trips (Fig. 7, Table 4). Julian Sprung (2004), a marine aquarium expert and author of several books on the topic, wrote an article in Advanced Aquarist Magazine detailing the life history traits and husbandry requirements for several octocoral species, providing aquarium hobbyists with a user's manual for maintaining octocorals. By 2006, an article describing octocoral propagation techniques was published in Reefkeeping (Hiller, 2006), another popular online marine aquarium magazine, making these techniques more widely accessible to the home hobbyist. Also during this time, the use of octocorals in seahorse aquariums became popularized as images and discussions of "seahorse-friendly" organisms became trending topics in marine aquarium forums (www.reefcentral.com/forums, accessed in 2006). The collectors interviewed noted that requests for yellow octocorals increased during this same period, perhaps due to increased online forum traffic.

Since the mid-2000s, the demand for octocorals has declined annually, but the high price-per-unit has produced some of the highest grossing years since 1994 for octocoral collection, as reported in FWC Trip Ticket data. The estimated value of the octocoral fishery peaked at $145,759 in 2007 and $152,029 in 2008 (Fig. 7, Table 4). At the height of the recession in 2009, the price per colony declined to $0.67 and then increased from $1.15 to $4.08 in 2010. Demand dropped by 24% in 2010 (Fig. 7, Table 4). The need for collectors to generate lost income after the 2008 recession was likely the most important factor that drove prices upwards, but low demand by hobbyists reduced the number of colonies collected. The most recent data show a 13% increase in colony landings and a $0.33 increase in price per colony from 2011 to 2012 (Fig. 7, Table 4).

As reported in the FWC Trip Ticket reports (the following regional and species group specific data are unpublished), octocoral landings and dockside value data are available for Florida on a statewide basis (Fig. 8) and further partitioned for the Florida east (Fig. 9) and west coasts (Fig. 10). Approximately 80% of octocorals are collected from the Atlantic Ocean off the Florida Keys and the east coast of Florida from Monroe County to Palm Beach County. In Florida Keys northward to Palm Beach County, compared to other areas of Florida and the rest of the southeastern U.S., octocoral populations are diverse—species from all of the color groups (e.g., other, purple, and red) are collected (Fig. 9A). The smaller octocoral fishery on the west coast of Florida in Gulf of Mexico waters, concentrated mainly in Hillsborough and Pinellas Counties, is comprised mainly of octocorals in the "other" and "purple" categories. The taxa collected within the "red" species group are *Leptogorgia* species and *Muricea pendula* (Fig. 10A and Table 2). The "red" species

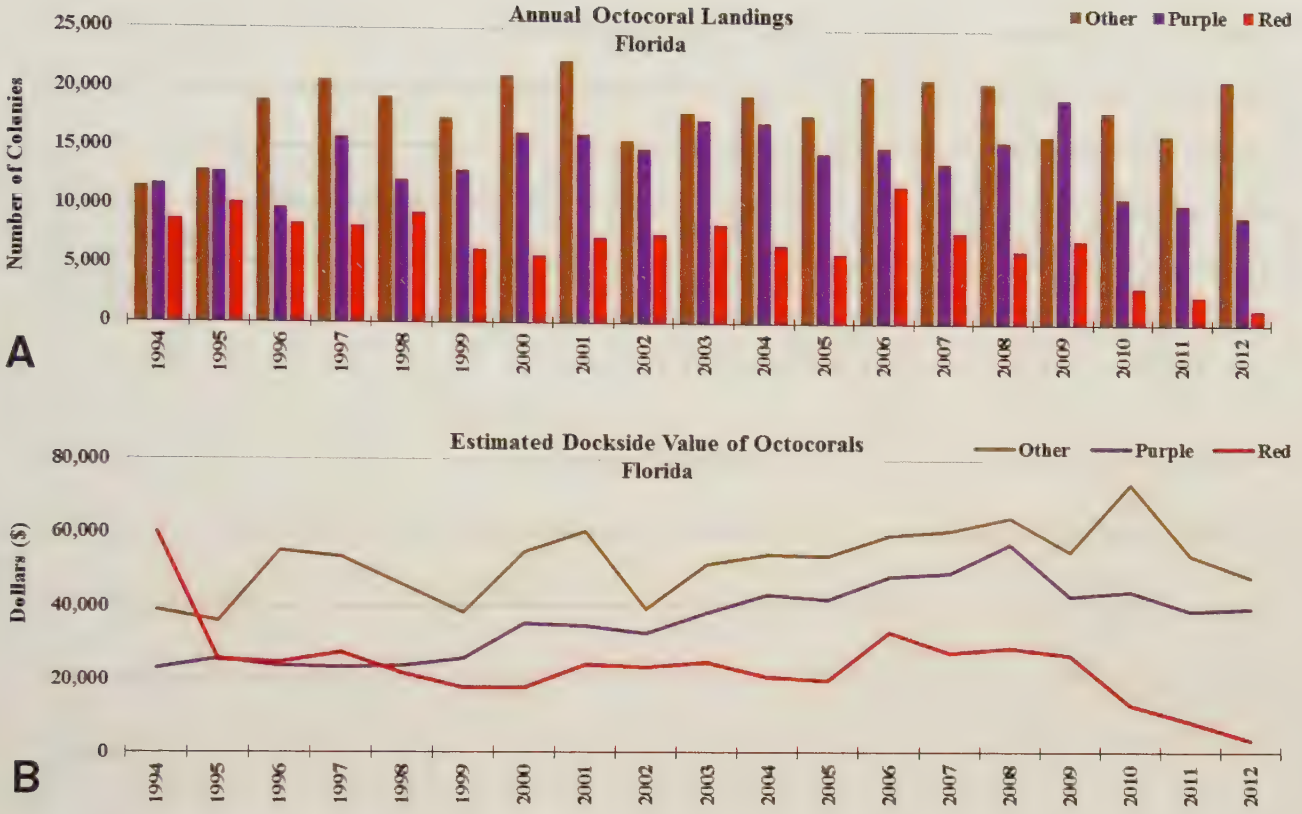


Figure 8.—(A) Annual octocoral landings and (B) dockside value of octocoral species groups (other, purple, and red) in State and Federal waters off Florida, 1994–2012 (FWC, 2014).

code elsewhere usually refers to *Swiftia exserta*, which has red polyps, but it is possible that other octocorals with a red rind or colony axis are reported under this code. Contrary to what would be expected from an industry that values colorful, seemingly rare species, the demand in the aquarium trade is primarily for octocorals in the "other" species group (Table 6). On average, nearly half (47%) of all of the octocorals collected annually are species within the "other" species group (18,340 octocorals), primarily (74%) on the Atlantic Ocean side of Florida (Table 6). However, on average they are sold at a lower price per unit than those collected on the Florida west coast ($2.67/colony vs. $3.75/colony) (Table 6). The difference in unit colony price has not hampered the value of "other" octocoral species collected in Atlantic waters; current (as of 2012) data show the greatest dockside value of octocorals ($48,128) compared to the value of "other" octocorals from the Gulf of Mexico ($25,955) (Fig. 9B and 10B).

Demand for "purple" octocorals began to increase in the early 2000s (Fig. 8), a period in which small (< 20 cm) whole colonies of *Antillogorgia* species, *Briareum asbestinum,* and *Pterogorgia anceps* were being sold to hobbyists as an alternative to the mostly brown octocorals sold within the "other" species group. However, the diversity of "purple" octocorals available was limited because of the difficulty in finding small, whole colonies suitable for home aquaria. After the 2008 economic recession, collectors began exploring alternative options for increasing the diversity of octocorals that could be brought to market. From this need to diversify and find new income sources, "Eco-Gorgs®" was developed. To create Eco-Gorgs®, several small (< 20 cm) clippings were removed from larger adult colonies (Fig. 4), glued to concrete plugs (Fig. 5), and marketed as a sustainable alternative to collecting whole colonies. Additional desirable species (color and/or large polyps) such as *Muriceopsis flavida* and *Plexaurella nutans* were then introduced to the market. Octocoral clippings had previously been introduced to the market in 1998, and while they were valued as having a relatively low impact on the ecosystem, they did not introduce any additional selection to the market. Increased interest in eco-friendly approaches and the introduction of new species to the market were what made Eco-Gorgs® more successful the second time around. The dockside market value of "purple"

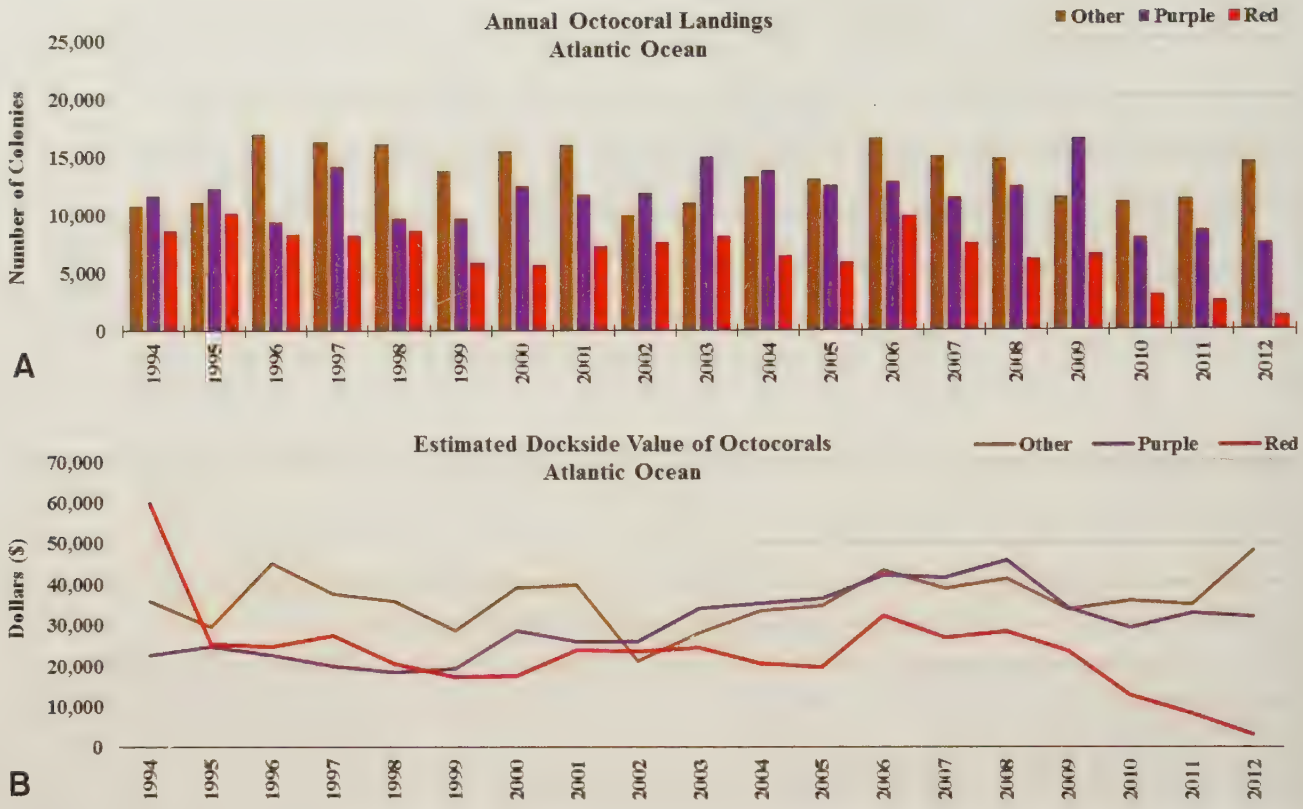


Figure 9.—(A) Annual octocoral landings and (B) dockside value of octocoral species groups (other, purple, and red) in State and Federal waters in the Atlantic Ocean off Florida, 1994–2012 (FWC, 2014).

Table 6.—Average annual landings (no. colonies), numbers of trips, price per colony, and economic dockside value of octocorals collected in Florida in the Atlantic Ocean and Gulf of Mexico during 1994–2012, based on unpublished commercial trip ticket data (FWC, 2014).

Area	Species group	Landings	No. of trips	Price/colony ($)	Value ($)
Atlantic Ocean	Other	13,569	351	2.67	36,018
	Purple	11,638	329	2.66	30,046
	Red	6,734	104	3.42	23,083
Gulf of Mexico	Other	4,771	190	3.75	17,897
	Purple	2,317	92	2.74	6,322
	Red	454	14	2.63	763

octocorals peaked in 2008 at $57,171 (Fig. 8B) and in 2009, demand for "purple" octocorals reached a high of 19,228 colonies (or fragments) collected (Fig. 8A).

Within the "purple" species group, eight species or taxa of octocorals are collected in Atlantic Ocean waters, three of which are also collected in the Gulf of Mexico: *Antillogorgia* species (sea plumes) and the sea whips *Pterogorgia anceps* and *P. guadalupensis* (Table 2). The greater diversity and abundance of "purple" octocoral taxa in the Atlantic supports 84% of the overall collection of these species (Table 6). Purple octocoral dockside values in the Atlantic surpassed that of the "other" octocoral species group from 2002–09 (Fig. 9B), while landings were greatest in 2009 (Fig. 9A). As of 2012, the average annual price per colony of "purple" octocorals was higher than any other year ($4.30/colony) for this and species collected within the "other" octocoral group complex.

Initial attempts in 1994 to make a large profit margin off the colorful "red" octocoral varieties (Table 2) by selling them at over $6.50/colony failed. The following year, "red" octocorals were sold at $2.48/colony and have since sold for an average of $3.14/colony. Though these octocorals fit the desired color profile of an ornamental organism, they are typically found at depths ranging from 25 to 60 m and may lack zooxanthellate. Without zooxanthellae, deepwater octocorals rely solely upon tentacle capture of plankton for their nutrition. Keeping deepwater octocorals in home aquaria therefore means hand-feeding the colonies live or frozen food mixtures. Presumably because they are more difficult to care for, demand for "red" octocorals declined in Florida by 75% since 2006 (Fig. 8A). Collection efforts have also declined from 272

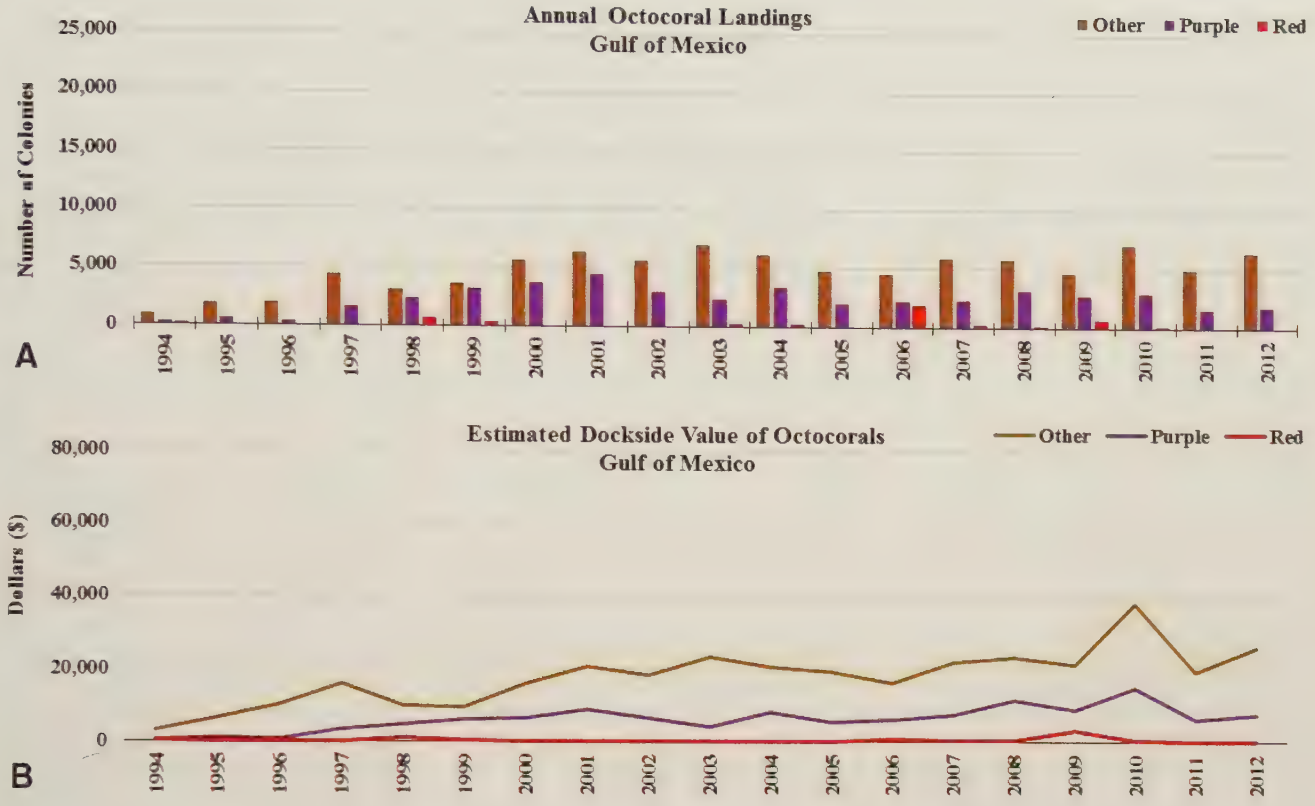


Figure 10.—(A) Annual octocoral landings and (B) dockside value of octocoral species groups (other, purple, and red) in State and Federal waters in the Gulf of Mexico off Florida, 1994–2012 (FWC, 2014)

trips annually in 2001 to 111 trips in 2012 (Sheridan[7]), with only a handful of collectors willing to work at deeper diving depths and with strong currents. Those that do collect deeper water colonies focus their efforts on the east coast of Florida off of Palm Beach, Broward, and Miami-Dade Counties. On average, 104 collecting trips are made annually, yielding 6,733 "red" octocorals with a dockside value of $23,082 (Table 6). In comparison, on average, 454 "red" octocorals (primarily *Leptogorgia* species, Table 2) were collected in the Gulf of Mexico during 10 out of the last 19 years, yielding an average annual dockside value of $763 (Table 6).

Biology and Ecology

Overview

A concern raised with the fisheries for marine ornamental, aquarium, and curio species in the U.S. South Atlantic and elsewhere is the lumping of species with potentially different biogeographic and habitat distributions, as well as life history parameters (e.g., growth and reproduction) in broad categories (Rhyne et al., 2009). The octocoral fishery in the U.S. South Atlantic and Gulf of Mexico, where the majority of the octocoral collection occurs in Florida waters, is no exception. Octocorals collected in Florida waters of the U.S. South Atlantic and Gulf of Mexico span genera and families that are categorized into color varieties for reporting under the FWC Trip Ticket program. Quotas and landings are presently designated into one of three color categories (purple, red, and other), although octocoral collectors often distinguish genera and species. FWC biologists have proposed a new reporting system based upon morphology (Brinkhuis[8]). At issue is that species with life history patterns that render them perhaps more resilient to collection (e.g., rapid growth, high recruitment, and broad distribution) are lumped with species that may be less resilient to over-collection because of slower growth, delayed reproduction, lower recruitment, slower regeneration from injury, and/or restricted geographic distribution or habitat/depth distribution. One goal of this study was to address the poor taxonomic

[7]Sheridan, N. 2014. Octocoral harvest from state vs. federal waters by Gulf of Mexico vs. Atlantic waters, 1994-2013. FWC unpubl. data, personal commun.

[8]Brinkhuis, Vanessa. Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Res. Inst., Personal commun., Oct., 2013.

resolution in the octocoral fishery to evaluate if sub-components of the fishery might be more or less sustainable, and thus perhaps require different management strategies. By addressing these data gaps and providing the best scientific information to the South Atlantic Fishery Management Council and the State of Florida, improved management of the octocoral fishery is a hopeful outcome, with ideally the least economic impact to the collectors that depend financially upon octocoral resources.

The narrative below provides an overview of octocoral biology and ecology, with a focus on those species targeted in the octocoral fishery in the U.S. South Atlantic and Gulf of Mexico. The number of species investigated was determined by consultation with collectors, as they are only required to note color categories on Trip Tickets, and available landings data from the State of Florida do not show any further taxonomic resolution. Dr. H. Feddern, an octocoral collector, indicated that he personally collects at least ten genera, with seven taxa identified to the species level from samples confirmed by State of Florida biologists using sclerite samples (Table 1). Further consultation and interviews with other collectors indicated a rather broad range of families, genera, and species that are targeted, represented by 15 genera and at least 23 species (Table 2). As most of these taxa are collected primarily in the Florida Keys, the focus of the overview of octocoral biology and ecology concerns those genera and species identified by collectors, along with sister taxa within genera in cases where only a genus (e.g., *Eunicea* spp. or *Muricea* spp.) was identified as being targeted. A substantial compilation of species-specific information is presented in the Appendix[9], which synthesizes much of the available information on geographic distribution, depth range, habitat, and life history information (e.g., growth, recruitment, and sources of mortality) for the main suite of octocorals collected for the marine life aquarium and ornamental trades in the U.S. South Atlantic and Gulf of Mexico. Much of the available literature stems from octocoral studies in Florida, as well as the wider Caribbean or tropical western Atlantic. Primary and gray literature sources were reviewed, along with field survey information, to compile species profiles (Appendix). Cairns et al. (2002) list 102 octocoral taxa for U.S. Atlantic waters out to the edge of the continental shelf, not including Puerto Rico and the U.S. Virgin Islands. Octocoral collectors in Florida target at least 23 species, not including species groups such as *Antillogorgia* spp., *Eunicea* spp., and *Muricea* spp. Information for 51 octocoral species among 16 genera was part of this study, including all of the targeted species in the octocoral fishery, as well as many sister taxa, especially where collectors noted genera instead of species.

[9]The appendix is available in the online version of this article (doi: https://doi.org/10.7755/MFR.80.3.2).

General Aspects of Biology

Octocorals include the soft corals, sea fans, blue corals, and sea pens and belong to the Phylum Cnidaria (Coelenterata), an ancient (pre-Cambrian) and diverse assemblage of mostly marine organisms also including jellies, sea anemones, corals, and hydroids (Fabricius and Alderslade, 2001; Cairns et al., 2002; Brusca and Brusca, 2003). Diversity within the phylum stems from two fundamental aspects of many cnidarian life cycles: 1) the tendency to form colonies by asexual reproduction and 2) dimorphic alternation of generations as polyps and medusa exhibited by some groups. Like other cnidarians, octocorals are diploblastic organisms (epidermis, gastrodermis, and mesoglea) at a tissue grade of construction, characterized by radial symmetry, tentacles, stinging structures (cnidae with nematocysts), an incomplete gastrovascular cavity with only one opening (the mouth), and a middle layer of mesenchyme or mesoglea (Brusca and Brusca, 2003). The mesoglea in octocorals, called the coenochyme, can contain fibers and skeletal elements consisting of calcareous spicules or sclerites (Lewis and Von Wallis, 1991). In most octocorals, the sclerites are arranged in three distinct layers in the coenochyme, generally small (0.05–1 mm), and produced by specialized cells (Lewis and Von Wallis, 1991). The outer cortex or surface layer of the octocoral colony can be variable in sclerite composition, but generally, only one type of sclerite occurs (Bayer, 1961). Octocoral sclerites, along with field characters such as branching patterns, are often needed to confirm field identification (Bayer, 1961).

Octocorals are modular organisms, similar to reef-building corals (Scleractinia), where the basic module is the polyp; growth is indeterminate, with no indication of senescence (Jackson, 1991). Thus, portions of a colony may die due to injury, overgrowth by other organisms, or predation (Jackson, 1991; Castanaro and Lasker, 2003). Octocorals are benthic, sessile, passive suspension feeders, but many species, especially in shallower water, derive nutrients from intracellular algae (zooxanthellae) and thus can be classified as zooxanthellate or azooxanthellate. Azooxanthellate corals rely solely on particle capture by the tentacles to fulfill their nutritional requirements.

Classification of octocorals, like for many groups of organisms, has undergone significant changes in the past decades, with various reclassifications and renaming (Bayer, 1961, 1981; Fabricius and Alderslade, 2001; Cairns et al., 2002). Besides scientific names, various common names are used by octocoral collectors, recreational divers, and scientists (Voss et al., 1969; Cairns, 1977; Cairns et al., 2002). Within the phylum, octocorals are grouped under the class Anthozoa that contains nine orders and ~6,000 extant species. Within the Class Anthozoa all of the octocorals are in the Subclass Octocorallia (=Alyconaria). They are characterized as colonial organisms containing polyps with eight hollow, marginal, and usually pinnate (feathery) tentacles, along with eight complete mesenteries, with free or fused

sclerites embedded in mesenchyme (Brusca and Brusca, 2003). The pinnate or feathery tentacles are covered with sensory cells and stinging capsules (cnidae), and may contain symbiotic algae (zooxanthellae). Stolons or coenochyme connect the polyps, with new polyps usually formed by budding from existing stolons. Octocorals comprise a diverse assemblage of organisms commonly referred to as soft corals, sea fans, gorgonians, blue corals, and sea pens. In the literature and in the vernacular, the term "soft coral" sometimes refers to Octocorallia, which have no massive skeleton or internal axis, but sometimes this term also includes sea fans (Fabricius and Alderslade, 2001). The term "sea fan" is sometimes used as an alternative for gorgonian, which are Octocorallia other than sea pens that grow upwards from the substratum with the support of an internal axis (Fabricius and Alderslade, 2001).

Soft corals and gorgonians were formerly classified separately in the Orders Alcyonacea and Gorgonacea, respectively; however, they are now grouped together under the Order Alcyonacea (Bayer, 1981; Fabricius and Alderslade, 2001; Cairns et al., 2002). Most of the octocorals collected for the marine aquarium and ornamental (curio) trades in the U.S. South Atlantic and Gulf of Mexico consist of sea whips, sea rods, and sea plumes, distributed among 4 suborders and 12 families (Cairns et al., 2002). Colonies are usually brightly colored and arborescent with a firm internal axial skeleton composed of horny proteinaceous material (gorgonin) that contains modified collagen and may be mineralized. Occasionally the skeleton is calcareous, but colonies are always covered with a thin layer of sclerite-filled mesoglea, which provides colony support and protection (Bayer, 1961; Lewis and Von Wallis, 1991). Surface sclerite (spicule) shape is used to identify octocorals (Bayer, 1961), along with patterns in the colony growth axis (Cairns, 1977). Octocoral growth morphology and even the structure of the spicules can vary over different depth and water flow regimes (Bayer 1961; Lewis and Von Wallis 1991). Octocorals are one of the more difficult groups of organisms to identify, and may explain why the Federal and State of Florida reporting requirements currently consist of color categories.

Biogeography

Octocorals are broadly distributed in the marine environment, present in every ocean basin from the tropics to polar regions, from the intertidal zone to abyssal depths (Bayer, 1961; Fabricius and Alderslade, 2001). The western central Pacific harbors the greatest number of octocoral species (90 genera and 23 families), but the western Atlantic also include a relatively high number of species (Bayer, 1961; Cairns et al., 2002). The American Fisheries Society (AFS) Committee on Common Names of Aquatic Invertebrates (CNAI) lists 102 octocoral taxa for U.S. Atlantic waters (exclusive of Puerto Rico and the U.S. Virgin Islands) that inhabit contiguous shore waters on or above the continental shelf to a depth of 200 m. The focus herein is on geographic distributions pertaining to those genera and species targeted by the octocoral fishery from North Carolina to Texas, with a particular emphasis on south Florida.

Broad-scale (i.e., wider Caribbean) geographic patterns of 51 octocoral species are listed in Table 7. The majority of shallow-water (< 20 m depth) species have a relatively broad distribution across the wider Caribbean, largely mirroring the distribution patterns of stony corals, concentrated in warmwater (18–31°C) regions, possibly due to the relatively narrow temperature tolerance of microalgae (zooxanthellae) (Fabricius and Alderslade, 2001). Approximately 170 species of gorgonian octocorals occur in the West Indian Province (wider Caribbean), which includes Bermuda, the Bahamas, the Greater and Lesser Antilles, south Florida, the Gulf of Mexico, and the Caribbean coasts of Central and South America (Cairns, 1977). Many of these taxa (~100) occur below 50 m depth and/or are found in temperate waters (Bayer, 1961; Cairns et al., 2002). Taxa with deeper depth distributions, beyond where most octocoral surveys are conducted, often have sparse or no biological information (see Appendix).

Habitat and Depth Distribution

In subtidal habitats, specifically in areas with available hard substratum, octocorals can reach densities approaching 100 colonies/m^2 (Yoshioka, 1998). Environmental parameters such as light, water depth, water motion, sedimentation, and availability of appropriate substrata are the most important determinants of octocoral distribution. For zooxanthellate species, the light regime, influenced by depth and water clarity, but also substratum steepness and stability, are important factors in spatial distribution. In azooxanthellate octocorals, larvae preferentially settle in low light microenvironments and depend on particle capture to meet nutritional requirements. Octocorals can flourish in areas with strong currents and light to moderate wave action. Many species require consistent and moderately strong currents to maximize food encounter rates (Fabricius and Alderslade, 2001). This is most evident, for example, in sea fans, where colony orientation is perpendicular to the predominant current direction to maximize food particle interception. Stronger currents not only transport food towards and waste away from colonies, but also stimulate photosynthesis. Tolerance to sediment loads varies widely among octocoral taxa, with some adapted to clearer waters, while others flourish in moderately turbid waters. Some azooxanthellate species are quite abundant in turbid environments (Opresko, 1973; Fabricius and Alderslade, 2001).

Life History

Life history refers to an organism's lifetime pattern of growth, development, and reproduction, reflected in an array of adaptations relating to physiology, morphology, and behavior. Life history includes traits that

Table 7.—Biogeography of octocorals (Cnidaria, Anthozoa, Alcyonaria = Octocorallia) in the Wider Caribbean, with a focus on taxa occurring on the Atlantic and Gulf coasts of Florida, especially those collected for the marine aquarium/curio trade (shaded). Asterisks (*) indicate the most demanded taxa in the U.S. South Atlantic octocoral fishery. Species are grouped by suborders and families according to Cairns et al. (2002).

	Wider Caribbean region[1]							
Octocoral species	1	2	3	4	5	6	7	8
Suborder Scleraxonia								
Family Briareidae								
Briareum asbestinum		X	X	X	X	X	X	
Family Anthothelidae								
*Diodogorgia nodulifera**	X	X		X	X	X	X	
Erythropodium caribaeorum	X	X	X	X	X	X	X	
Iciligorgia schrammi		X	X	X		X	X	
Suborder Holaxonia								
Family Plexauridae								
Eunicea asperula	X	X	X	X				
E. calyculata	X	X	X	X		X	X	X
*Eunicea (=Plexaura) flexuosa**	X	X	X	X		X	X	X
E. fusca		X	X	X		X	X	X
E. knighti	X	X	X		X		X	X
E. laciniata	X	X	X	X		X	X	
E. mammosa		X	X		X		X	
E. palmeri		X	X				X	
E. succinea		X	X	X	X		X	
E. tourneforti	X	X	X	X	X	X	X	
Muricea atlantica	X	X	X	X		X	X	X
M. elongata	X	X	X	X	X		X	X
M. laxa	X	X	X	X		X	X	X
M. muricata		X	X		X		X	X
M. pendula								
M. pinnata								
*Muriceopsis flavida**		X	X	X		X	X	
M. petila		X	X			X		
Plexaura kuna (=Plexaura A)		X						
P. homomalla		X	X	X		X	X	X
Plexaurella dichotoma		X	X	X		X	X	X
P. fusifera	X	X	X		X		X	X
P. grisea		X	X	X		X	X	
*P. nutans**	X	X	X	X		X	X	X
P. pumila		X	X			X	X	X
Pseudoplexaura crucis		X		X		X	X	
P. flagellosa		X	X	X		X	X	X
P. porosa		X	X	X		X	X	X
P. wagenaari	X	X		X		X	X	X
*Swiftia exserta**		X				X		
Family Gorgoniidae								
*Antillogorgia (=Pseudopterogorgia) acerosa**	X	X	X	X	X	X	X	X
A. americana		X	X	X	X	X	X	X
A. bipinnata		X	X	X	X	X	X	
*A. elisabethae**		X	X			X	X	
*A. kallos**		X				X		
A. rigida	X	X	X	X	X	X	X	
Gorgonia flabellum		X	X		X	X	X	
G. ventalina		X	X	X		X	X	X
Leptogorgia (=Lophogorgia) cardinalis	X	X				X	X	
L. punicea								
L. virgulata	X			X			X	
*Pterogorgia anceps**		X	X	X		X	X	
*P. citrina**		X	X	X		X	X	X
P. guadalupensis	X	X		X		X	X	
Suborder Calcaxonia								
Family Ellisellidae								
Ellisella barbadensis	X	X			X	X	X	
E. elongata		X	X				X	X
Ellisella (=Nicella) schmitti		X					X	

[1](1) Gulf of Mexico, including the west coast of Florida, (2) southeastern Florida including the Florida Keys, (3) Bahamian archipelago (Bahamas and Turks and Caicos), (4) Hispaniola, Puerto Rico, U.S. Virgin Islands, (5) Antillean (Lesser Antilles from the British Virgin Islands to Barbados and Grenada), (6) NW Caribbean (Cuba, Jamaica, Cayman Islands, Caribbean coast of Mexico, and Belize), (7) Continental Caribbean (Honduras to Suriname, including Trinidad, Tobago, Aruba, Bonaire, and Curacao), and (8) Bermuda.

affect an organism's "schedule" of reproduction and survival; how an organism reproduces (including reproductive mode); timing of reproduction in relation to environmental factors, age, or size; frequency of reproduction (semalparity vs. iteroparity); type of larval output (internal brooding vs. external spawning and development); and number of offspring produced per reproductive episode. Life history also includes adaptations relating to an organism's interactions with other organisms.

Most marine populations, including octocorals, are dynamic in both space and time. Survival of adults is one of the principal factors affecting popula-

tion changes. For example, if survival of adults is high, then the current population size plays a significant role in explaining the population size in the future. As many octocorals brood larvae, often throughout the year, once an assemblage of reproductive colonies is established, it tends to persist. At the same time, the generation of offspring and survival of young are also important.

Age and Growth

Growth rate data are limited for most octocoral species (Cary, 1914; Yoshioka and Yoshioka, 1991). Colony growth is usually estimated by changes in colony height. Like other modular organisms, such as stony corals, there is high variability in growth and size is often a poor indicator of colony age (Yoshioka and Yoshioka, 1991). In general, faster-growing octocoral species tend to be found at higher densities (Yoshioka, 1997). Previous studies suggest a general pattern of relatively low mortality and high variability in octocoral growth rates (Yoshioka and Yoshioka, 1991), with variability in growth roughly equivalent to average growth increments. Thinly branched taxa, such as *Antillogorgia* and *Muricea* species, can grow up to 4 cm/yr, while thicker branched species, such as *Plexaurella,* barely grow 1 cm/yr (Yoshioka and Yoshioka, 1991). Birkeland (1974) recorded a mean growth of 2.6 ± 1.9 cm (mean ± 95% CI) for the common sea fan, *Gorgonia ventalina*, over a 230-day period off coastal Panama. Birkeland (1974) recorded an annual growth rate of 2 cm/yr for the same species in the Cayman Islands. Yoshioka and Yoshioka (1991) studied a multi-species octocoral assemblage on two shallow-water reefs (< 10 m) off the southwest coast of Puerto Rico over a 4.5-yr period. Growth rates, as determined by changes in colony heights, ranged from 0.8–4.5 cm/yr among 12 taxa. The mean growth rate was 1.4–2.6 cm/yr for most species, ranging from a low 0.8 cm/yr in *Plexaurella dichotoma* to a high of 4.5 cm/yr in *Antillogorgia americana*. Uninjured colonies generally grew faster than injured colonies, thus sublethal injuries were concluded to be partly responsible for intra-specific variation in growth (Yoshioka and Yoshioka, 1991). Thinly branched species (*A. acerosa* and *A. americana*) are relatively fast growing, while species with thicker branches (e.g., *P. dichotoma*) grow slower, presumably representing a trade-off between colony branch elongation and branch thickening (Yoshioka and Yoshioka, 1991).

Reproduction and Recruitment

Like many marine invertebrates, octocorals exhibit a two-stage (bi-partite) life cycle, consisting of a benthic, sessile stage (post-settlement juvenile to adulthood) and a planktonic larval stage (planula). The oval-shaped, featureless planula larvae settle out from the water column, with the spatial pattern of settlement influenced by substratum type, light intensity, and integrity (Wahle, 1985). Crustose coralline algae are preferred substrate for octocoral recruitment (Benayahu et al., 1989; Lasker and Kim, 1996). In contrast, the presence of algal films or sediment can impede recruitment and/or lead to greater post-settlement mortality (Gotelli, 1988). Upon settlement, the planula larvae metamorphose into a founder polyp, initially forming a short stalk at one end that is attached to the substratum. The other polyp end flattens and eight tentacle buds develop around the mouth opening (Fabricius and Alderslade, 2001). Within a few days, a complete octocoral polyp develops; at this stage, some zooxanthellae species begin to take in planktonic zooxanthellae through the mouth (the zooxanthellae are not digested, but are incorporated into the octocoral tissue), while in other species, the larva are supplied with zooxanthellae prior to their release into the water column (Benayahu et al., 1992). Although a few deeper water octocoral taxa remain permanently solitary as single polyps, all other octocorals develop from a solitary founder polyp and form colonies derived from budding (Fabricius and Alderslade, 2001).

Octocorals typically reach sexual maturity when colonies are over 20 cm in height. *Pterogorgia citrina,* a small bushy octocoral that rarely grows above 30 cm in height, may reach sexual maturity sooner, but little is known about this species. To provide adequately sized octocorals to home aquarists, collectors typically take colonies that are less than 20 cm in height. In doing so, collectors leave larger colonies behind that are the major contributors of gametes to the population. For example, colonies of *Eunicea flexuosa* over 70 cm in height produce 93–98% of the eggs released during spawning (Beiring and Lasker, 2000). The octocoral collectors interviewed indicated that they rotate collection sites and are selective in which colonies they collect.

Asexual reproduction is common in octocorals (Fabricius and Alderslade, 2001) and often the predominant mode of reproduction, but not in all species (e.g., *Leptogorgia virgulata*, Gotelli, 1988). In asexual reproduction, colonies may form runners or stolons from the base of the colony, or extend branches out from the colony. The parent colony then translocates parts of its own body mass through the stolon, and a new daughter colony forms that separates from the parent. The stolon is then resorbed, resulting in two colonies. Octocorals also can bud, fragment, and undergo colony fission, where constrictions are formed in the colony and eventually divide into two independent smaller colonies. In budding, small buds are produced on the edge or base of a colony, which eventually drop off and attach to the substratum as separate colonies. Some species are known to drop polyp bundles consisting of 5–10 polyps that sink to the substratum, or by "autonomy of colony ends" (i.e., fragmentation sensu Walker and Bull, 1983).

Octocorals sexually reproduce using a diversity of strategies paralleling scleractinian reef-building corals (Kahng et al., 2011). Most octocorals have male and female reproductive structures in separate colonies, which is referred to as the gonochoristic mode of reproduction (Fabricius and

Alderslade, 2001). Three types of sexual reproduction have been identified in octocorals: broadcasting (broadcast spawning) of eggs and sperm, internal brooding of larvae, and external brooding of larvae (Benayahu and Loya, 1984; Benayahu, 1991; Lasker and Stewart, 1992). Broadcast spawning has been observed in alcyoniid soft corals and some gorgonians, which release large numbers of eggs and sperm into the water where external fertilization occurs. Spawning is often synchronized according to lunar phase and/or water temperature. Subsequently, planula larvae develop from fertilized eggs and remain in the plankton for days to weeks until settlement and metamorphosis into founder polyps. Larvae may be carried a considerable distance—tens to hundreds of km away from the parental colonies based upon oceanographic conditions (Gotelli, 1988). Some species (i.e., *Plexaura kuna* and *Eunicea fusca*) exhibit multiple strategies, reproducing sexually (brooding or broadcast spawning) and asexually through fragmentation and vegetative propagation (Kahng et al., 2011), which can support high population growth rates (Lasker, 1988).

Like scleractinian corals, the demography of octocorals, including sexual maturity and reproductive output, may be more based upon size (height) rather than age (Wahle, 1983; Kapela and Lasker, 1999). Octocorals have size-dependent reproduction ability, although some (e.g., *Leptogorgia virgulata*) may be reproductively competent within two years of settlement (Gotelli, 1988), while other taxa may not reach reproductive competence until much later post-settlement (Beiring and Lasker, 2000).

Internal brooding of larvae is common in many gonochoristic octocorals (e.g., family Xeniidae), including some taxa in the wider Caribbean (Brazeau and Lasker, 1990). Sperm are released into the water (not the eggs), usually a few hours after sunset, and the eggs that are fertilized develop into larvae within the female colonies. Larvae are released days to weeks later and are ready or nearly so for metamorphosis. A final reproductive strategy within the octocorals is the external brooding of larvae. The fertilized eggs develop into larvae within mucus pouches on the surfaces of the mother colonies (Brazeau and Lasker, 1990). Brooded larvae, which are negatively buoyant, may settle within a few meters of the mother colony.

Existing information on octocoral recruitment and post-settlement mortality suggests that, in contrast to established adult colonies, post-settlement mortality can be quite high. For example, Gotelli (1988) observed that ~64% of *Leptogorgia virgulata* recruits did not survive the first year after settlement. With established populations, survival of additional post-settlement octocoral recruits is generally higher, while survival of established, larger colonies (10+ cm in height) may be more or less constant (~94% per yr) (Yoshioka, 1998). While established colonies may or may not be a key factor underlying octocoral population fluctuations, they are essential to the persistence of populations (Yoshioka, 1998).

Mortality Rates, Sources of Mortality, and Regeneration from Injury

Lacking major disturbances, such as storms and disease outbreaks, octocorals appear to exhibit low mortality rates from the few studies available. Over a 230-day period off the coast of Panama, for example, Birkeland (1974) documented > 95% survivorship of sea fans (*Gorgonia ventalina*). Probably the most comprehensive study of survivorship rates in a multispecies octocoral assemblage is the work of Yoshioka and Yoshioka (1991). At two sites on the southwestern coast of Puerto Rico, they recorded an annualized survivorship rate of 91.6–92.4%, with no significant differences among the 12 octocoral taxa sampled. Sublethal (i.e., not whole colony) injuries were responsible for some of the high intra-specific variation in growth; uninjured colonies generally grow faster than injured colonies (Yoshioka and Yoshioka, 1991).

Sources of octocoral mortality include detachment from the substratum (Wahle, 1985), fracture of the skeleton, overgrowth (Wahle, 1980), disease outbreaks (Naglelkerken et al., 1997), and thermal stress (Lasker, 2005). Octocorals are susceptible to abrasion and dislodgement by storm waves and associated movement of sand and rubble (Wahle, 1985; Fabricius and Alderslade, 2001). Some Caribbean octocorals (e.g., encrusting *Briareum* and *Erythropodium*), along with some branching species, especially sea fans (*Gorgonia* spp.), are quite abundant in wave-exposed environments. However, many octocorals are more abundant in less wave-exposed environments, including lagoon patch reefs and deeper fore-reef habitats (Fabricius and Alderslade, 2001). In shallower water, sea fan colony orientation is perpendicular to current direction (Wainwright and Dillon, 1969), presumably an adaptation to high wave-energy conditions and to maximize food particle interception.

Sediment burial and abrasion stress are important sources of mortality for both established colonies and newly settled recruits (Gotelli, 1988), along with weakening of the substratum (Yoshioka and Yoshioka, 1991). Colony detachment generally results from the failure of the underlying substrate rather than the colony holdfast (Cary, 1914; Kinzie, 1973; Birkeland, 1974). The major source of mortality (40–71%) in one study (Yoshioka and Yoshioka, 1991) was due to basal fracture (breakage of the axial skeleton near the colony base (22–46%) where greater rates were attributed to higher wave energy. Injury to the colony basal tissue caused by physical abrasion increases the probability that a colony will eventually experience basal fracture (Yoshioka and Yoshioka, 1991). Detachment and basal fracture are largely non-selective among octocoral species and are not likely due to predation (Harvell and Suchaneck, 1987; Lasker and Coffroth, 1983; Yoshioka and Yoshioka, 1991).

Ecological and Economic Roles of Octocorals

Most octocorals are suspension feeders, obtaining small food particles from the water column. The octocoral diet consists of small (< 20 μm) particulate organic matter such as bacteria, phytoplankton cells, and zooplankton (Fabricius and Klumpp, 1995; Fabricius et al., 1995; Ribes et al., 1998). Most of the food captured is assimilated near the point of ingestion (Murdoch, 1978). Larger particles that encounter tentacles are captured and swallowed if suitable, typically consisting of early crustacean and bivalve larval stages (Fabricius et al., 1995; Ribes et al., 1998). As octocoral nematocysts are relatively small compared to jellies, hydroids, and sea anemones (Fabricius and Alderslade, 2001), particle capture is restricted to smaller food items. The octocoral epidermis is covered with microvilli, so absorption of dissolved organic matter is likely an additional food source (Schlichter, 1982). Octocoral feeding rates are affected by food concentrations and currents (Fabricius et al., 1995).

Azooxanthellate octocorals, because they do not harbor zooxanthellae, obtain all of their nutrition by suspension feeding. Many shallow-water octocorals host symbiotic algae (zooxanthellae, Dinoflagellata) to supplement their dietary needs and are thus light dependent (Kinzie, 1973). Zooxanthellae are embedded in gastrodermal cells or in membrane-bound vacuoles within the gastrovascular cavity. Zooxanthellate octocorals utilize photosynthetic products from their microalgae to contribute to their energy needs, but still must rely upon particle capture by the tentacles (Fabricius and Klumpp, 1995). Octocorals apparently have a lower photosynthetic efficiency that may be related to the low surface area of octocoral colonies in relation to biomass (i.e., photosynthetic yields are low and respiration rates are relatively high) (Fabricius and Alderslade, 2001). Most zooxanthellate octocorals generally expand their tentacles and feed during the day, yet some species have a reverse pattern, possibly due to strong or slack current flow, high irradiance, and/or disturbance by predators (Fabricius and Alderslade, 2001). Preston and Preston (1975) found that the degree of polyp extension in an assemblage of mostly zooxanthellate octocorals was related to plankton availability, but light intensity was most important in daily activity patterns.

Because branching octocorals grow upright from the substratum, they offer a canopy structure that provides habitat for a diversity of invertebrates and fishes (Cairns, 1977; Wahle, 1980). Patton (1972) documented animal symbionts on *Leptogorgia virgulata* from the northern Gulf of Mexico, while Spotte and Bubucis (1996) described the caridean shrimps associated with *Antillogorgia americana*.

From the information compiled on octocorals as represented in the Appendix, it is clear that many information gaps exist, particularly growth, age, longevity, mode of reproduction, and recruitment rates for deeper-water taxa. There are relatively few long-term studies of growth and survivorship (Yoshioka and Yoshioka, 1991), and most studies of octocoral species or assemblages have been short in duration (< 1 yr) and usually limited to one or a few species (Yoshioka and Yoshioka, 1991).

Analysis of Current Data Collection Programs

Current data collection programs for octocoral management in the U.S. South Atlantic and Gulf of Mexico were reviewed as part of this study, particularly fishery independent studies in southeast Florida and the Florida Keys, since most octocorals are landed from these areas. The narrative below, along with the management recommendations section, addresses the following questions raised about the U.S. South Atlantic octocoral fishery. First, is the level of data collected at the State of Florida and Federal levels sufficient to effectively manage the octocoral fishery? Second, does existing information on octocoral abundance and distribution lead to a better understanding of the octocoral fishery and potential management improvements or alternatives? Next, is the current octocoral fishery reporting structure sufficient, or are there changes to implement that would improve management or understanding of the fishery? Relatedly, is there a need for an octocoral species identification guide to help standardize reporting requirements in the U.S. South Atlantic? Finally, what fishery-independent assessment and monitoring data are available for octocorals in the region that provide octocoral population-level assessments? Are these efforts adequate to assess the status of populations using current data from the octocoral fishery?

The marine aquarium trade has both commercial and recreational components, and similar to other fisheries, is complex in terms of the diversity and number of invertebrate and fish species targeted, the different types of gear and approaches used to capture organisms, geographic areas, and access points (Bohnsack et al., 1994). There is a long history of marine life collection that dates back to at least the 1960s in the south Florida area, where a diversity of invertebrate and fishes were collected, primarily for the marine aquarium industry but also for the curio trade (Voss et al., 1969; Jaap and Wheaton, 1975; Robins, 1976; Derr, 1992; Bohnsack et al., 1994). Some of these activities are now managed, including the moratorium on sea fan collection, restrictions on live rock collection, and prohibitions on the use of chemicals for collecting (FAC Chap. 68B-42). In Florida waters, the collection of live tropical, ornamental, and marine species such as fish, invertebrates, and plants is regulated by FAC Chap. 68B-42. Implementation of the "Marine Life Rule" went into effect in 1991 and has undergone subsequent amendments. Bag limits, collection techniques, and area restrictions have been set for recreational and commercial marine life collectors in both Federal and Florida waters, and included restricted collection of certain species

and licensing and endorsement requirements. Octocorals are currently considered to be ornamental species. Historical (Bohnsack et al., 1994) and current collection levels (FWC, 2014), in terms of numbers of individuals or colonies removed, are lower than for most other marine life fishery species and groups (Table 4).

The historical and current reporting structure for the Florida marine life fishery dating back to 1990 consists of landings by numbers of individuals or colonies, as opposed to the sizes and/or weights of organisms captured (Bohnsack et al., 1994; FWC, 2014). Exceptions to this pattern are for marine plants (weight) and live rock (weight or number of boxes) when this was permitted. Since 1990, octocoral landings, which are reported as the number of colonies collected, are grouped into broad categories based on color (e.g., yellow, purple, or red), growth form (e.g., sea blades), or other (Bohnsack et al., 1994; FWC, 2014). In Florida, landings were initially reported from the county where an organism was first sold, not necessarily where an organism was collected. The FWC currently collects octocoral data in terms of numbers of colonies collected, number of collection trips, average price per colony, and average dockside value of colonies. On both the Florida Atlantic Ocean and Gulf of Mexico coasts, information gathered from octocoral collectors indicates that among these color groupings, there are at least 29 octocoral species among 19 genera, with at least 12 nominal taxa (species and/or genera) characterized as in high demand (Tables 1 and 2).

There are aspects of octocoral biology and ecology that are relatively similar across taxa, such as the need for stable hard substrata for settlement and growth. On the other hand, some species exhibit differences in habitat distribution and life history parameters such as growth rate and reproduction. For many of the targeted taxa, there is a paucity of available information on habitat distribution, population abundance, and life history parameters, especially for species that have deeper depth distributions (e.g., *Diodogorgia*, *Ellisella*, *Iciliogorgia*, and *Swiftia*). These taxa are under-sampled or are not targeted in historical and current assessment and monitoring programs. Despite these constraints, there is evidence that even some of the deeper water octocorals are broadly distributed and occur in high densities along much of the southeastern coast of the U.S. (David[10]). There are obvious gaps in knowledge related to the distribution and abundance of some octocoral genera and species. However, the relatively broad distribution of most octocorals in southeastern Florida and estimates of current population sizes presented below, relative to the small numbers of octocorals collected per year for most taxa, suggests that 1) additional reporting requirements, while desirable, may not be necessary, and 2) the octocoral fishery in Florida is sustainable. The number of octocorals collected in Florida appears to be a minor percentage (<0.1%) of the population abundance estimates, where they exist, for aggregate and individual taxa.

Fishery Independent Data Sources

Fishery-independent assessment and monitoring available for octocorals in the U.S. South Atlantic and Gulf of Mexico regions are described below, with a focus on results that provide population-level assessments for octocorals. Results address whether or not these data are adequate to assess the status of octocoral populations in the absence of finer-resolution fishery-dependent data from the octocoral fishery. As most octocorals are collected in southeastern Florida from Palm Beach County to Monroe County (Table 5), the focus of this section provides an overview of historical and current studies of octocorals in the area. Sampling efforts are briefly reviewed that provide data on geographic distribution, habitat and depth distribution, colony density, colony size structure, and population abundance estimates.

For the southeastern Florida and Florida Keys areas, the available information on octocoral population parameters (distribution, density, size structure, and abundance estimates) can be summarized as follows. First, most surveys of octocorals were conducted in relatively shallow-water (< 15 m) hard-bottom and coral reef habitats, although a few studies surveyed deeper hard-bottom and reef environments (e.g., Goldberg, 1973; Wheaton, 1981, 1987). Second, most historical studies conducted species inventories of octocorals in one or more habitats, with information presented as species presence or absence (e.g., Voss and Voss, 1955; Voss et al., 1969; Davis, 1982; Wheaton, 1987; reviewed in Levy et al., 1996). Third, relatively few historical and more recent studies have quantified octocoral colony density (numbers of colonies per unit area) by habitat and depth (e.g., Goldberg, 1973; Opresko, 1973; Kissling, 1977; Jaap, 1984; Wheaton and Jaap, 1988; Chiappone and Sullivan, 1994), and these studies have typically been of limited duration (< 2 yr). A few sampling efforts provide estimates of octocoral holdfast or canopy cover, but, except for encrusting species, they do not provide information on octocoral densities (Chiappone and Sullivan, 1997; Ruzicka et al., 2009; Gilliam, 2012). Even fewer studies recorded octocoral size (height) structure for branching octocorals species (e.g., Opresko, 1973). A small number of projects such as the Coral Reef Evaluation and Monitoring Program (CREMP), Broward County's Marine Biological Monitoring Program, and local academic institutions, through the use of permanently marked sampling locations, have monitored changes in octocoral canopy cover and/or colony densities either annually or intermittently, dating back in some cases to the mid-1990s (Blair and Flynn, 1989; Moyer et al., 2003; Beaver et al., 2006; FWC, 2006; Thanner et al., 2006; Gilliam et al., 2007). Finally, only one program to our knowledge has used a survey sampling design, structured

[10]David, Andrew. NOAA Natl. Mar. Fish. Serv., Panama City, FL. Personal commun., Nov. 2014.

by habitat, depth, geographic region, and management zone, to quantify octocoral densities that can be scaled to abundance estimates (Miller et al., 2002; Smith et al., 2011).

The majority of available information on octocorals in Florida consists of species lists or inventories from various studies, dating back to the 1950s (e.g., Bayer, 1961), combined with information on habitat and depth distribution (reviewed in Levy et al., 1996). These surveys were usually conducted within a proposed or existing protected area such as: Biscayne National Monument (now Biscayne National Park) (Voss et al., 1969; Jaap, 1984), Ft. Jefferson National Monument (now Dry Tortugas National Park) (Davis, 1982), Key Largo National Marine Sanctuary (now the Key Largo Management Area), Looe Key National Marine Sanctuary (now the Looe Key Management Area) (Antonius et al., 1978; Wheaton and Jaap, 1988), and Florida state parks (John Pennekamp Coral Reef State Park). Most historical octocoral studies report species occurrences related to benthic habitat types; these data are largely captured in the life history summaries in the Appendix. In other instances, taxonomic or field guides provide more general geographic distribution patterns (e.g., Bayer, 1961; Cairns, 1977; Colin, 1978). With few exceptions, species inventories were usually in shallow-water (< 15 m) hard-bottom and reef habitats. In the early 1970s, however, Goldberg (1973) conducted stony coral and octocoral surveys to 44 m depth off Palm Beach County (described below). In 1975, Wheaton (1981) conducted qualitative surveys (species identification and photographs) at Carysfort Reef in the upper Florida Keys using replicate belt transects sampled to 21 m depth and recorded 27 taxa. Additional visual surveys of octocorals using a submersible were conducted in 1979 at French Reef, Elbow Reef, and Carysfort Reef within the Key Largo Coral Reef Marine Sanctuary at depths of 27–56 m (Wheaton, 1987).

Further north along the southeastern Florida reef tract from Miami-Dade to Palm Beach Counties, Banks et al. (2008) summarized several studies describing hard-bottom and reef community structure (Goldberg et al., 1973; Blair and Flynn, 1989; Moyer et al., 2003; Beaver et al., 2006; FWC, 2006; Thanner et al., 2006; Gilliam et al., 2007). Historical surveys of octocorals north of the Florida Keys are somewhat limited. Goldberg (1973) conducted benthic surveys of stony corals and octocorals on nearshore patch reefs (9 m depth), the outer reef from 16–30 m depth, and the fore reef (32–44 m depth) off Boca Raton, Florida. Octocoral diversity (39 species) and densities were high (25 colonies/m^2). The greatest octocoral diversity occurred on the outer reef where the convergence of shallow and deepwater octocorals occurs from 15–30 m depth. Faunal cover for some habitats is similar to that further south in the Florida Keys, with hard-bottom areas often dominated by octocorals and sponges. Octocorals in the genera *Eunicea* and *Muricea*, along with *Briareum asbestinum,* are the dominant taxa from the 48 species reported. Based on averages of data collected by Blair and Flynn (1989), Thanner et al. (2006), and Gilliam et al. (2007), octocoral density throughout the southeastern Florida reef tract is approximately 7.7 colonies/m^2. Some areas in Palm Beach County have densities of more than 30 octocoral colonies per m^2 (Gilliam et al., 2003), while hard-bottom habitats off Miami-Dade County have octocoral densities between 2.9–21.2 colonies/m^2 (Blair and Flynn, 1989).

Broward County's Marine Biological Monitoring Program monitors the status and trends of coral and hard-bottom communities. Since 1997, the Broward County Department of Planning and Environmental Protection and the National Coral Reef Institute at Nova Southeastern University have quantified octocoral densities along belt photo-transects at 25 permanent sites on the nearshore and offshore reef terraces (Gilliam et al., 2004a). At these sites, octocoral density was 8.9 ± 13.9 colonies/m^2 and as high as 30 colonies/m^2 (Gilliam et al., 2003; Sathe et al., 2008).

Further south in the Florida Keys, several historical surveys provide octocoral distribution and density data from nearshore hard-bottom and patch reef environments (Voss and Voss, 1955; Opresko, 1973; Chiappone and Sullivan, 1994). Chiappone and Sullivan (1994) conducted presence-absence and density surveys of stony corals and octocorals at several nearshore hard-bottom and patch reef sites in the middle Florida Keys. Average octocoral densities ranged from 0.02–4.3 colonies/m^2, with the lowest species richness and colony densities on either nearshore hard-bottom habitat in Florida Bay, or on patch reefs dominated by massive corals. On the Atlantic Oceanside, hard bottom habitat exposed to moderately strong tidal flow was dominated by the genera *Eunicea*, *Pseudoplexaura*, and *Briareum*.

On Florida Keys patch reefs, historical surveys, mostly from Biscayne National Park (BNP), as reported by Opresko (1973), Jaap and Wheaton[11], and Jaap (1984), show variable octocoral densities ranging from 6.9–46.8 colonies/m^2. *Antillogorgia americana*, *Briareum asbestinum*, *Eunicea flexuosa*, *E. succinea*, *Gorgonia ventalina*, and *Plexaura homomalla* were the most dominant among 29 species present (Opresko, 1973). Wheaton (unpubl. data as reported in Wheaton and Jaap (1988)) observed 31 species in similar habitats in the Biscayne National Park area during surveys conducted over five years. In hard-bottom areas of Biscayne National Park, including nearshore tidal passes, beneath bridges, and seaward of the intertidal zone, octocoral densities were 38.3 colonies/m^2 and on transitional bank reefs, densities were 25.2 colonies/m^2 (Jaap, 1984).

Surveys conducted at six sites within Looe Key National Marine Sanctu-

[11]Jaap, W. C., and J. L. Wheaton. 1977. Unpublished report to the National Park Service on coral research in Biscayne National Monument. Cited In J. Dupont, W. Jaap, and P. Hallock. 2008. A retrospective analysis and comparative study of stony coral assemblages in Biscayne National Park, FL (1977–2000). Carib. J. Sci. 44:334–344.

ary reported mean octocoral densities ranging from 1.1–20.6 colonies/m^2 (Wheaton and Jaap, 1988). Of the 23 octocoral species observed, *Eunicea flexuosa, E. succinea,* and *Plexaura homomalla* comprised nearly 55% of the octocoral fauna. Additional species recorded in relatively high densities were *Antillogorgia americana, Gorgonia ventalina,* and *Muricea atlantica* (Wheaton and Jaap, 1988).

The CREMP, spearheaded by the Florida Fish and Wildlife Research Institute, has monitored the status and trends of 37 sites in the Florida Keys National Marine Sanctuary (FKNMS) since 1995 (Ruzicka et al., 2009) and in 2012 added an octocoral demographic survey component at a subset of sites from the upper Keys to the Dry Tortugas. In 2003, additional sites were added in Miami-Dade, Broward, and Palm Beach Counties as part of the Southeast Florida CREMP (SECREMP). This effort currently encompasses 17 sites (Gilliam et al., 2004b). Using video and still photography, benthic cover is assessed by identifying the major functional cover groups (macroalgae, sponges, stony corals, and octocorals) within replicate belt transects. Benthic cover by octocorals is similar throughout the Florida Reef Tract from Palm Beach County to the Dry Tortugas (Gilliam, 2012). Percentage cover by octocorals increased significantly since 2010 in parts of Miami-Dade County (12.8% in 2010 vs. 19.7% in 2011) and Broward County (5.4% in 2010 vs. 7.6% in 2011). In Palm Beach County, however, sites within each of the three reef tracts have shown a decrease in octocoral cover since the project's inception. Gilliam (2012) reported that several Palm Beach County study sites buried by sand, possibly from beach renourishment activities and/or storm events, may have contributed to the decreased octocoral cover.

Geographic Distribution and Density Patterns in the Florida Keys

From 1999–2014, the Sanctuary Coral Reef Evaluation and Assessment Monitoring (SCREAM) program conducted benthic surveys of algae, sponges, and cnidarians, including octocorals, in a broad range of hard-bottom and coral reef habitats from the northern extent of Biscayne National Park to the Dry Tortugas (Miller et al., 2002; Smith et al., 2011). Originally designed to document the status and trends of no-take management zones throughout the FKNMS, the program expanded to include multiple habitats from nearshore patch reefs to the deeper reef slope. By broadly sampling populations among multiple habitat types across the south Florida shelf, inside and outside of the no-take management zones, and throughout the Florida Keys from south of Miami to the Dry Tortugas, over a 15-yr period (including 2014 surveys of octocorals), this effort documented the distribution, abundance, and changes over time of coral reef organisms and communities in the region. In the section below, data are summarized related to octocoral surveys, including recently conducted surveys during June–October 2014. The surveys provide information on distribution, density, and population abundance estimates of Florida Keys octocorals.

The survey sample design is described in Smith et al. (2011) and parallels efforts for reef fish surveys in the south Florida region since the late 1990s. For octocorals, data have been collected on species presence-absence, colony densities, and colony heights. Briefly, a geographic information system (GIS) containing digital layers for benthic habitat, bathymetry, and management zone boundaries in the Florida Keys is used to facilitate delineation of the Florida Keys study area. Existing resolution of benthic habitat mapping is such that the survey domain was divided into a grid of individual cells 200 m x 200 m (40,000 m^2) that serve as primary sampling units. A two-stage sampling scheme was adapted (Smith et al., 2011) following Cochran (1977) and is employed to control for spatial variation in population metrics at scales smaller than the grid cell minimum mapping unit. Grid cells containing targeted reef and hard-bottom habitats are the primary sample units. A second-stage sample unit is defined as a belt transect of fixed area within a primary sample unit. The size of an individual primary sampling unit allowed divers to swim to the location of any given second-stage sampling unit from a moored or anchored vessel. During 1999–2004, octocorals were surveyed for colony densities in replicate 25 m x 0.4 m belt transects. From 2005–14, the belt transect survey area was reduced to replicate 8 m x 1 m samples per site based upon results from previous surveys that indicated slightly smaller sample sizes were sufficient to maintain targeted variance (measured as coefficient of variation). Within belt transect areas, octocorals are identified to the lowest taxonomic level possible (usually to the species level) and colonies (ramets) are counted. All visual surveys are conducted using SCUBA, pre-formatted data slates, pencils, and rulers. Results are transcribed the same day into a database to help facilitate quality control and quality assurance.

To control for spatial variation in the benthic variables assessed, the Florida Keys survey domain was partitioned into strata based upon: 1) habitat type and depth, 2) geographic region (along-shelf position), and 3) management zones comprising Biscayne National Park (BNP), areas outside of Florida Keys National Marine Sanctuary no-take zones, and Sanctuary no-take zones. Grid cells (sites) 200 m x 200 m in dimension are randomly selected from the combination of habitat type, regional sector, and management zone factors. Habitats are designated using regional benthic habitat maps. The habitat classification scheme accounts for features that correlate with benthic faunal distributions, including cross-shelf position, topographic complexity, and the proportion of sand interspersed among hard-bottom structures. A geographic regional stratification variable (i.e., upper, middle, and lower Florida Keys) was used to account for oceanographic and geological features in the Florida Keys that influence the distribution and com-

Table 8.—Sampling effort for octocorals in the upper Florida Keys from northern Key Largo to Upper Matecumbe Key during June–October 2014. The number of sites available represents the number of 200 m x 200 m mapping grid cells based upon existing habitat mapping and bathymetry data. Two 8 m x 1 m belt transects were surveyed for octocoral densities and colony sizes.

Benthic habitat type	No. sites available	Habitat area (m^2)	No. sites sampled	Area sampled (m^2)
Inshore patch reefs	2	80,000	2	32
Mid-channel patch reefs	622	24,880,000	17	272
Offshore patch reefs	940	37,600,000	26	416
Back-reef rubble	62	2,480,000	7	112
Inner line reef tract	97	3,880,000	11	176
High-relief spur and groove	111	4,440,000	16	256
Low-relief hard-bottom (< 6 m)	513	20,520,000	3	48
Low-relief spur and groove (6–15 m)	367	14,680,000	10	160
Low-relief hard-bottom (6–15 m)	480	19,200,000	4	64
Patchy hard-bottom (6–15 m)	98	3,920,000	6	96
Total	3,292	131,680,000	102	1,632

munity composition of hard-bottom and reef habitats. Management zones are incorporated as a third stratification variable that delineates areas open and closed to consumptive activities. The power of the stratified random sampling approach is two-fold: 1) the habitats comprising the most area are initially allocated more sites than those with less area (i.e., a proportional design); and 2) habitats exhibiting more variability with respect to particular metrics (e.g., coral species richness, octocoral density) are allocated more sites than those with less variability.

The habitats sampled during 1999–2014 incorporate most of the hard-bottom and coral reef habitat types from the island platform (e.g., inshore patch reefs such as Tavernier Rocks) inshore of Hawk Channel to ~15 m depth along the Florida Keys, including the Dry Tortugas. Benthic habitats surveyed for octocorals include inshore patch reefs, mid-channel patch reefs, offshore patch reefs, reef rubble, shallow (< 6 m) hard-bottom, shallow (< 6 m) spur and groove, and deeper fore-reef habitats (low-relief spur and groove, consolidated hard-bottom, patchy hard-bottom) from 6–15 m depth. In certain years, deeper habitats were sampled to 27 m depth. The underwater surveys occurred at randomly selected, pre-determined coordinates, located with a differential global positioning system. If the original waypoint was not the intended habitat type, based on visual assessment by a snorkeler or boat observers, the closest alternate site was sampled instead. Once on-site, a two- or three-person dive team deployed two transect tapes. For octocorals, an 8 m x 1 m belt area was surveyed along two transects.

Statistical analyses using this two-stage sampling design are based upon Cochran (1977) and Smith et al. (2011). Density and abundance calculations are based upon the number of organisms recorded within the belt transect stations. First, density (no. of octocoral colonies/m^2) is calculated for each transect. Next, mean density and variance are calculated for each site, using the densities of the two stations. The mean site-level densities and variances are then used to calculate mean stratum-level (habitat, management zones, and habitat by management zone) densities and variances. Finally, stratum-level and domain abundance estimates are calculated based upon the stratum-level densities and variances, as well as the proportional areas of each stratum within the domain (Smith et al., 2011).

Octocoral survey data (species richness, octocoral densities, and in some cases colony heights) from this program were derived from the following efforts from 1999–2014:

- 1999: 80 sites from northern Key Largo to Key West and 23 additional sites in the Dry Tortugas;
- 2000: 45 sites from Big Pine Key to Key West and 36 additional sites in the Dry Tortugas;
- 2001: 86 sites from northern Key Largo to Key West;
- 2005: 195 sites from northern Biscayne National Park to Key West;
- 2006: 46 sites in the Dry Tortugas;
- 2008: 145 sites from northern Key Largo to Key West and 43 additional sites in the Dry Tortugas;
- 2009: 160 sites from northern Key Largo to Key West; and
- 2014: 102 sites from northern Key Largo to Upper Matecumbe Key (see Table 8).

Data presented in this section represents a small proportion of the overall sampling effort, but illustrate three important aspects of octocorals in the Florida Keys, with a particular focus on those taxa (species, genera, and color groups) targeted by the octocoral fishery. First, most octocoral taxa (genera and species) are broadly distributed on the south Florida shelf. The availability of hard substratum appears to be one of the most important factors affecting the spatial distribution of octocorals. Second, changes in octocoral densities from 1999–2014 indicate either no significant temporal patterns or increases for many taxa. Finally, population abundance estimates, integrating density estimates with habitat area, indicate that octocoral populations are either stable or have increased during the past 15 years. Population sizes for many taxa are quite large (tens to hundreds of millions of colonies).

It is noteworthy that this sampling program does not specifically target nearshore hard-bottom or seagrass matrix habitats, where, for example, some octocorals such as *Pterogorgia anceps* and *P. guadalupensis* can be abundant (Voss and Voss, 1955; Voss et al., 1969; Chiappone and Sullivan, 1994). Deeper-water (> 20 m) habitats are also excluded for most years, which means that taxa in the "red" collector group are usually not encountered (e.g., *Iciliogorgia schrammi* and *Swiftia exserta*). In addition, the Florida Keys surveys are limited to just a small portion of the Florida coastline and thus do not include certain taxa (e.g., *Leptogorgia*) that are distributed

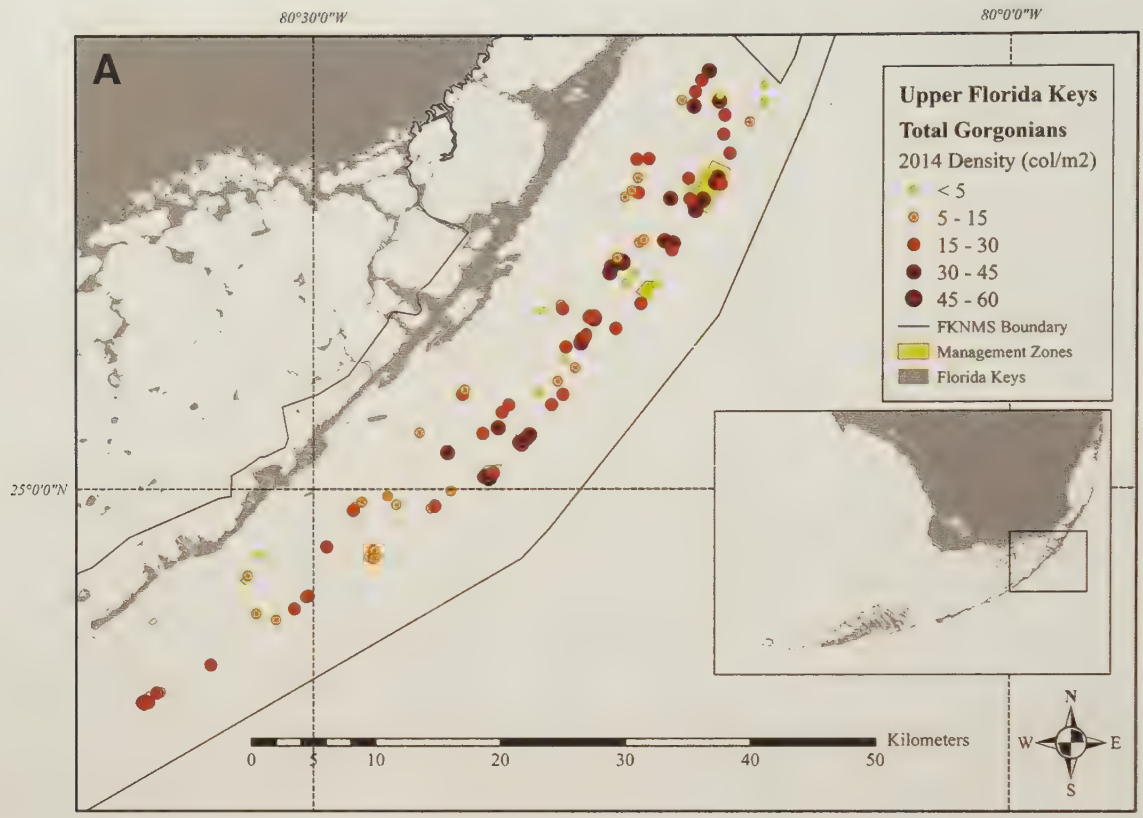


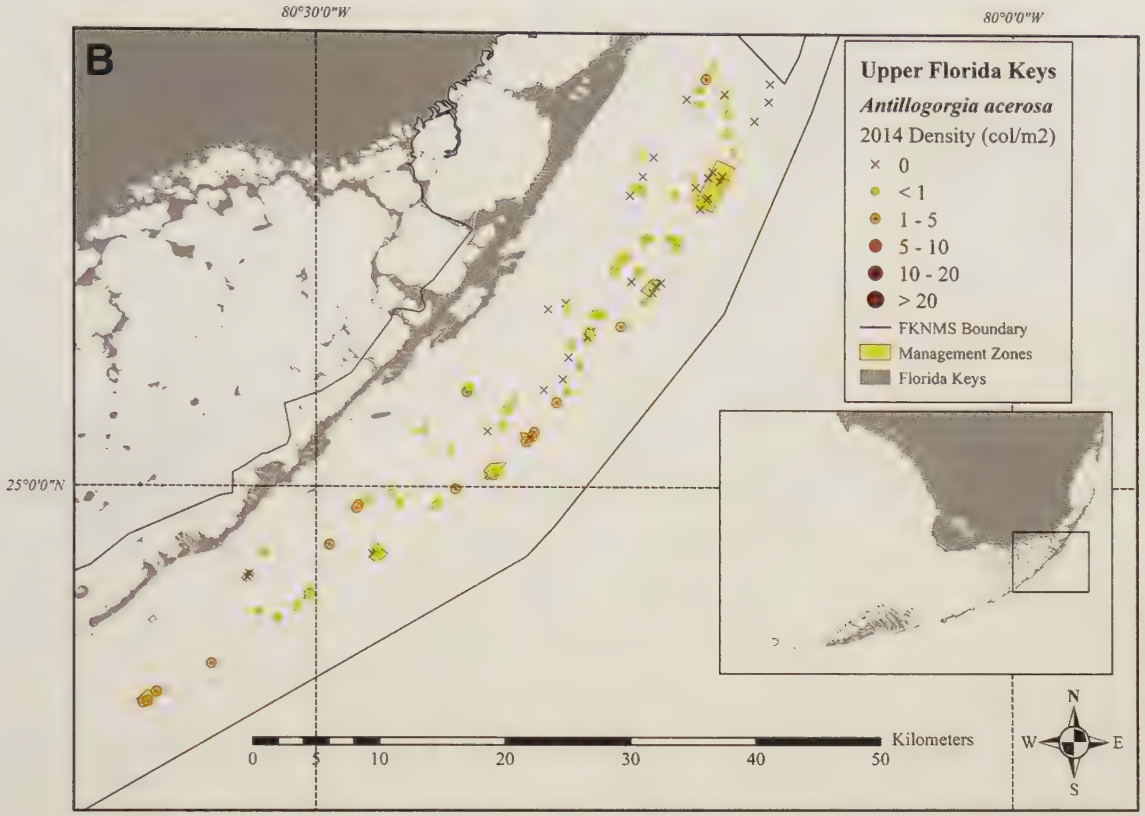
Figure 11.—Density (no. colonies/m^2) distribution maps A) for all encountered branching octocoral species combined and B–P) alphabetically by species in the upper Florida Keys from Carysfort Reef to Alligator Light, based upon surveys of replicate 8 m x 1 m belt transects sampled per site at 102 hard-bottom and reef sites during June–October 2014. *Figure 11 continues on next eight pages.*

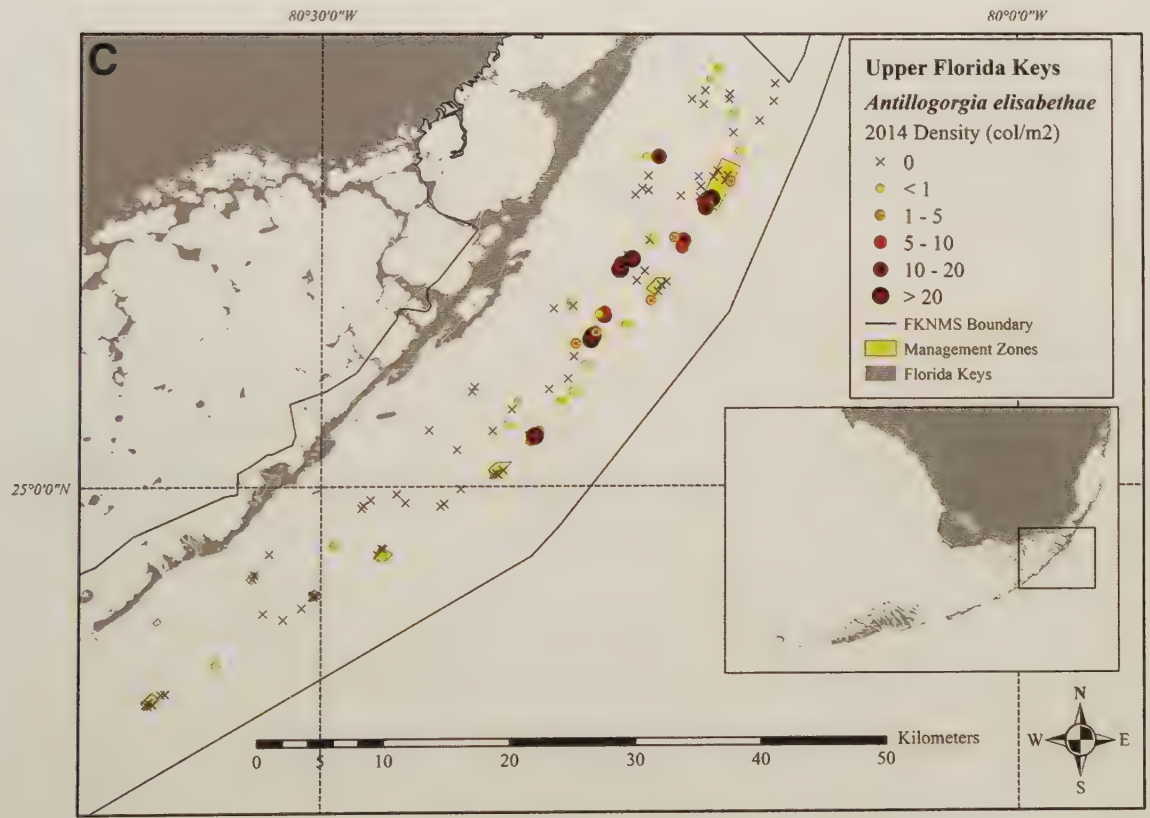
further north in warm-temperate environments on both the Atlantic and Gulf of Mexico coasts.

An example of the fishery independent octocoral data are presented below for the upper Florida Keys from Carysfort Reef to inshore of northern Key Largo (Carysfort Reef), southwestwards to Alligator Light to inshore of Upper Matecumbe Key. This represents a small proportion of the Florida Keys reef tract, much less the southeastern Florida coast, but illustrates some of the basic patterns in octocoral distribution, density, and population sizes that help to place the octocoral fishery and historical and current collection levels into perspective. These data include the longest time series available and the most current data available (2014) for octocorals the authors are aware of for the area.

Figure 11 illustrates the density distribution patterns of octocorals in the upper Florida Keys (northern Key Largo to Upper Matecumbe), based upon surveys from June–October 2014 (Table 9). The density distribution maps indicate that for all octocoral species combined, including those that are targeted in the octocoral fishery, most species are broadly distributed across the south Florida shelf. A few species, such as *Antillogorgia kallos*, *Pterogorgia anceps* and *P. guadalupensis*, appear to be relatively rare, but this may be due to the exclusion of nearshore hard-bottom and seagrass-hard-bottom matric habitats in the survey design and/or the extremely patchy nature of some octocorals. Improving population estimates for species that are patchy or rare requires adding more sites (possibly hundreds) to the sample design, increasing the costs and amount of in-water effort for the overall survey.

Figure 12 and Table 9 show density estimates combined for all habitats surveyed in the upper Florida Keys area for the following sample periods: 1999–2002 (combined), 2005, 2009, and 2014. For the collector color groups, overall mean densities for individual taxa and for combinations of taxa in color categories either have shown non-significant temporal changes or have increased (Table 9). Colony density increases occurred in nearly all of the taxa under the purple color category, in addition to non-targeted taxa. The relative density of





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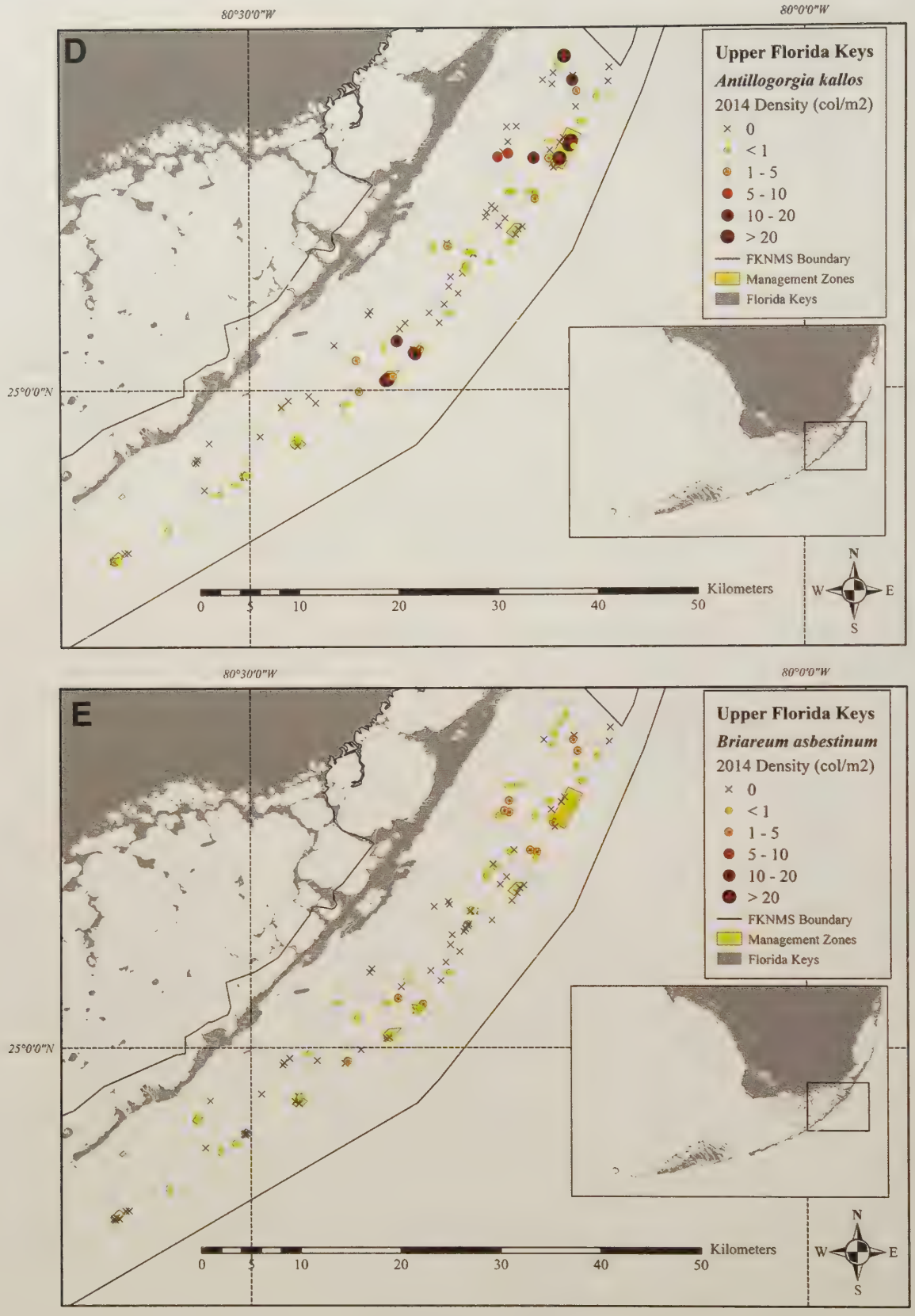

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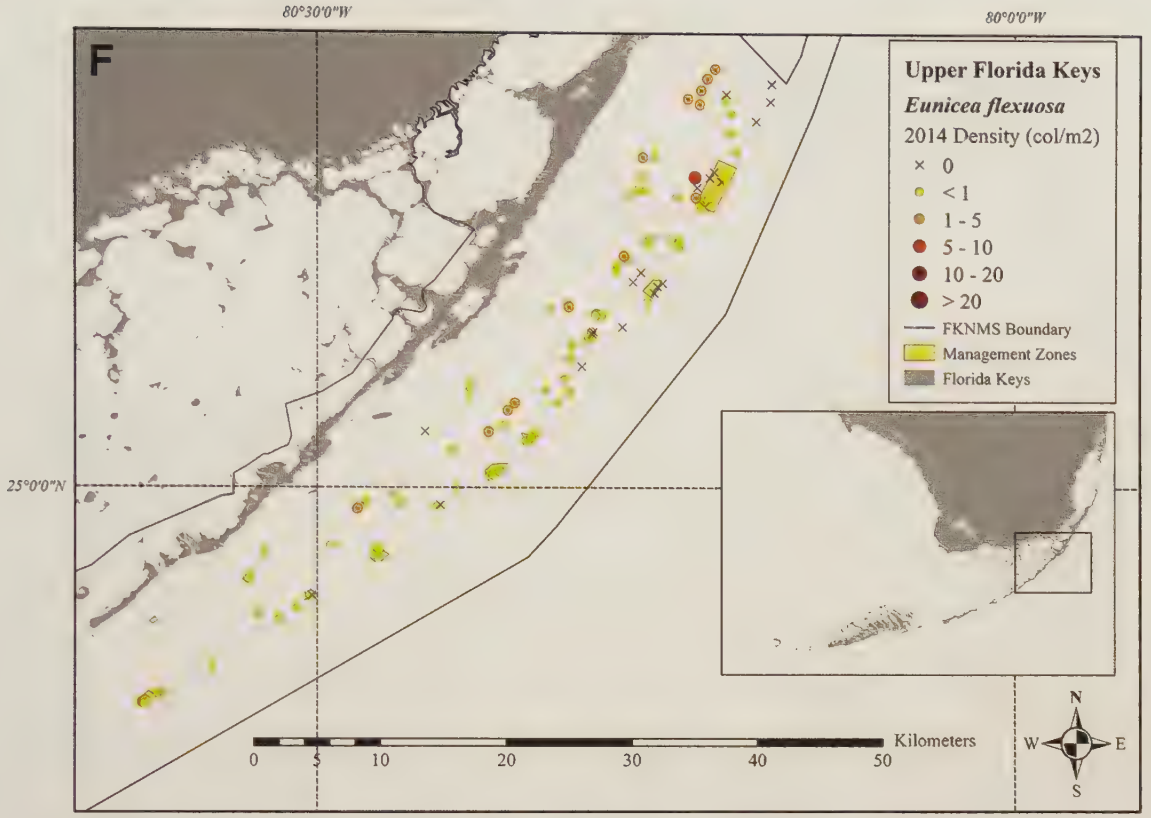

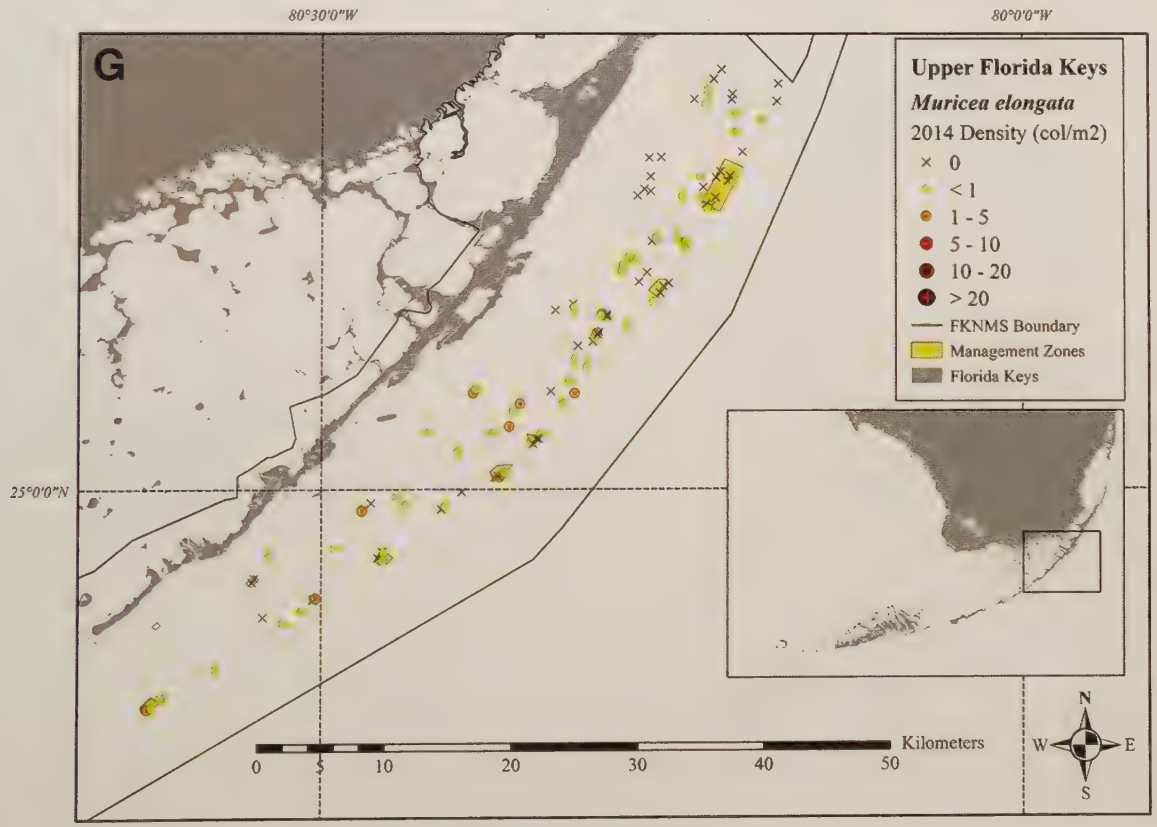

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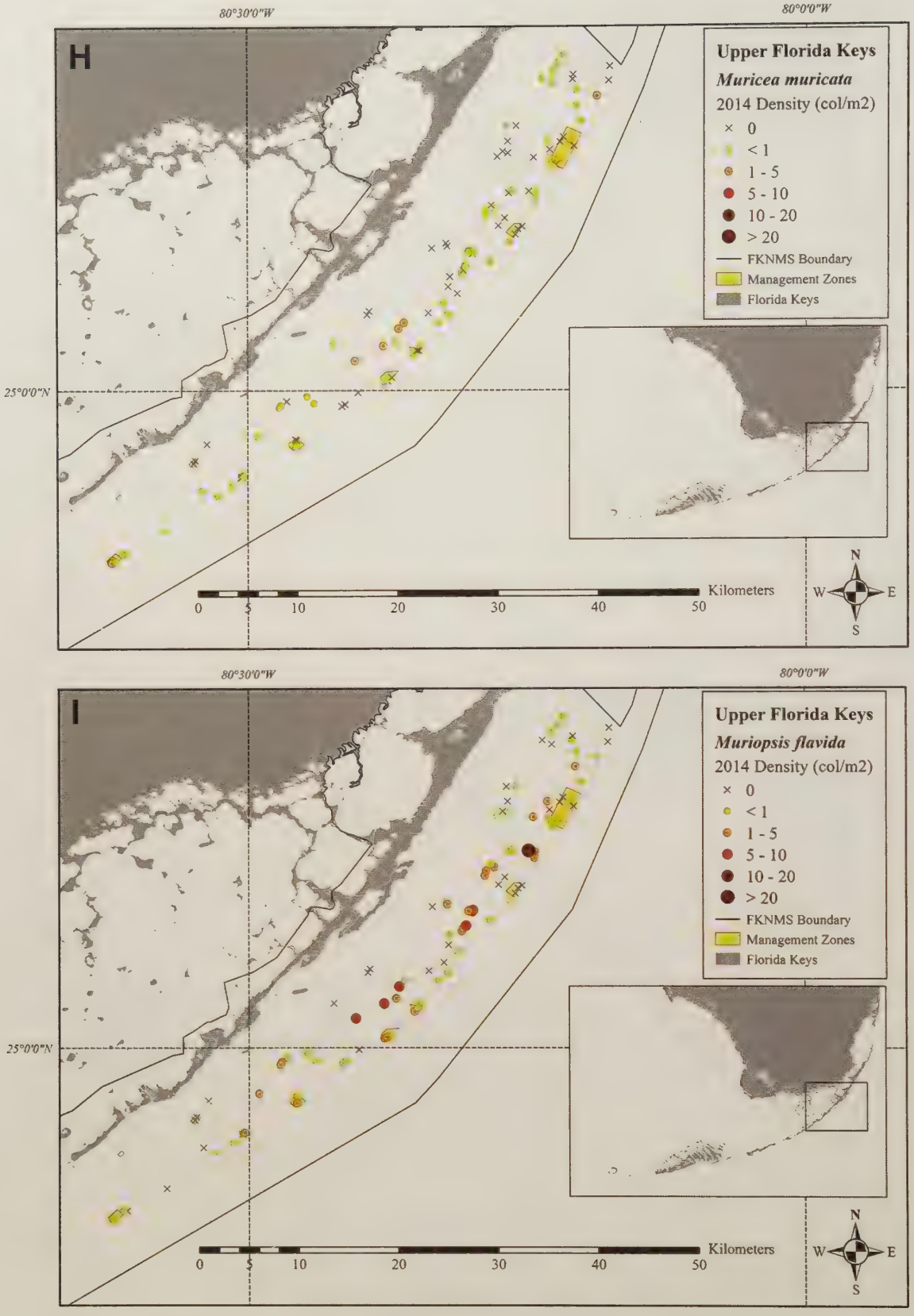

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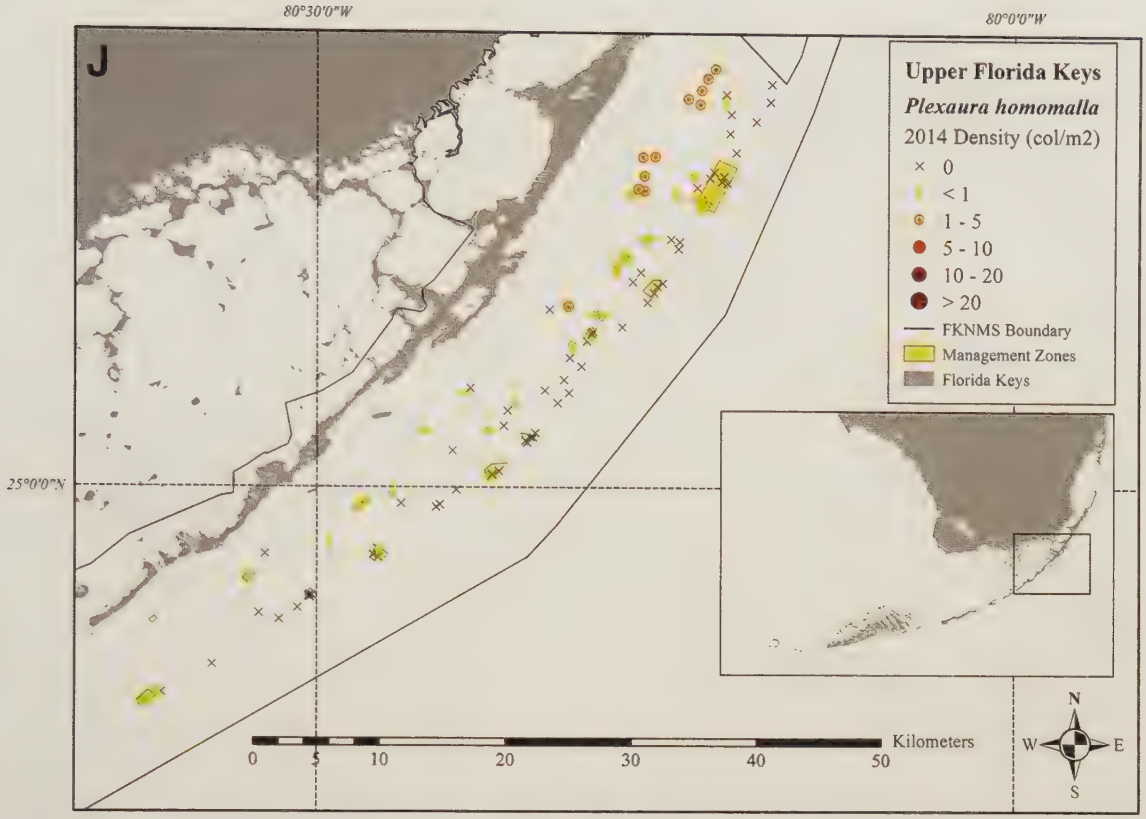

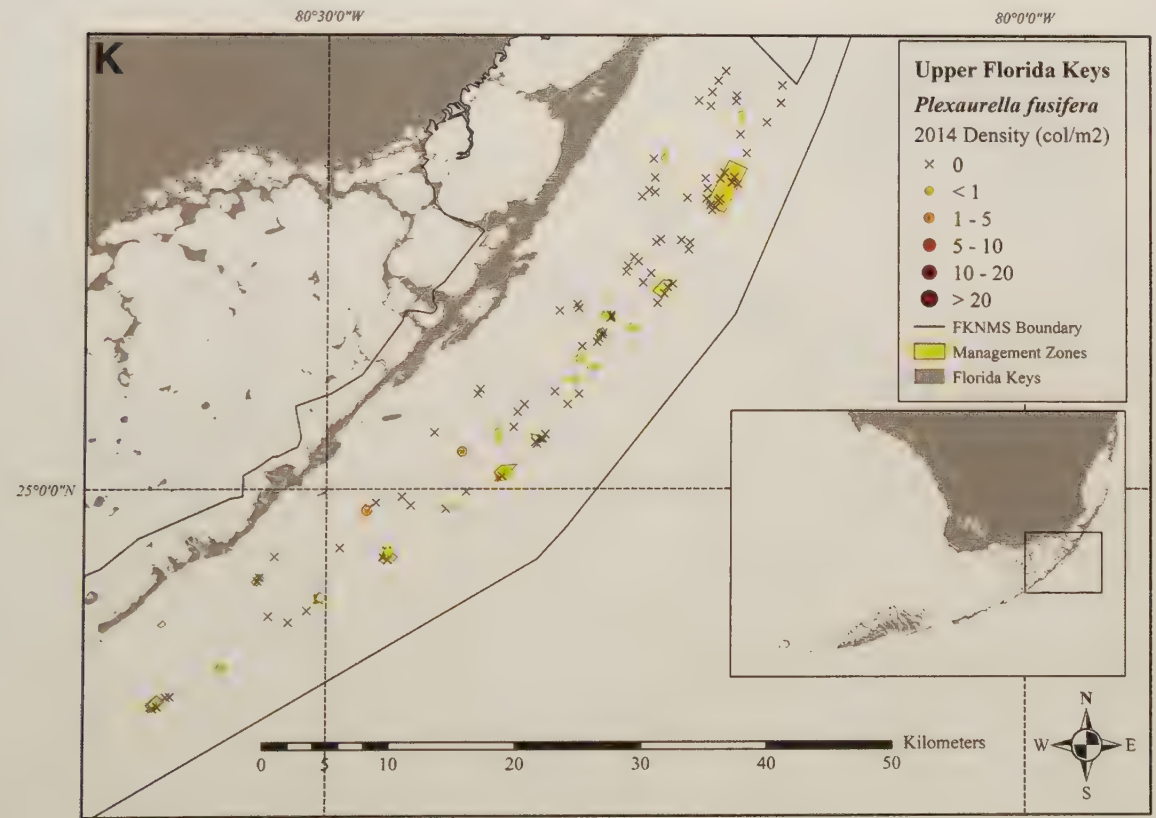

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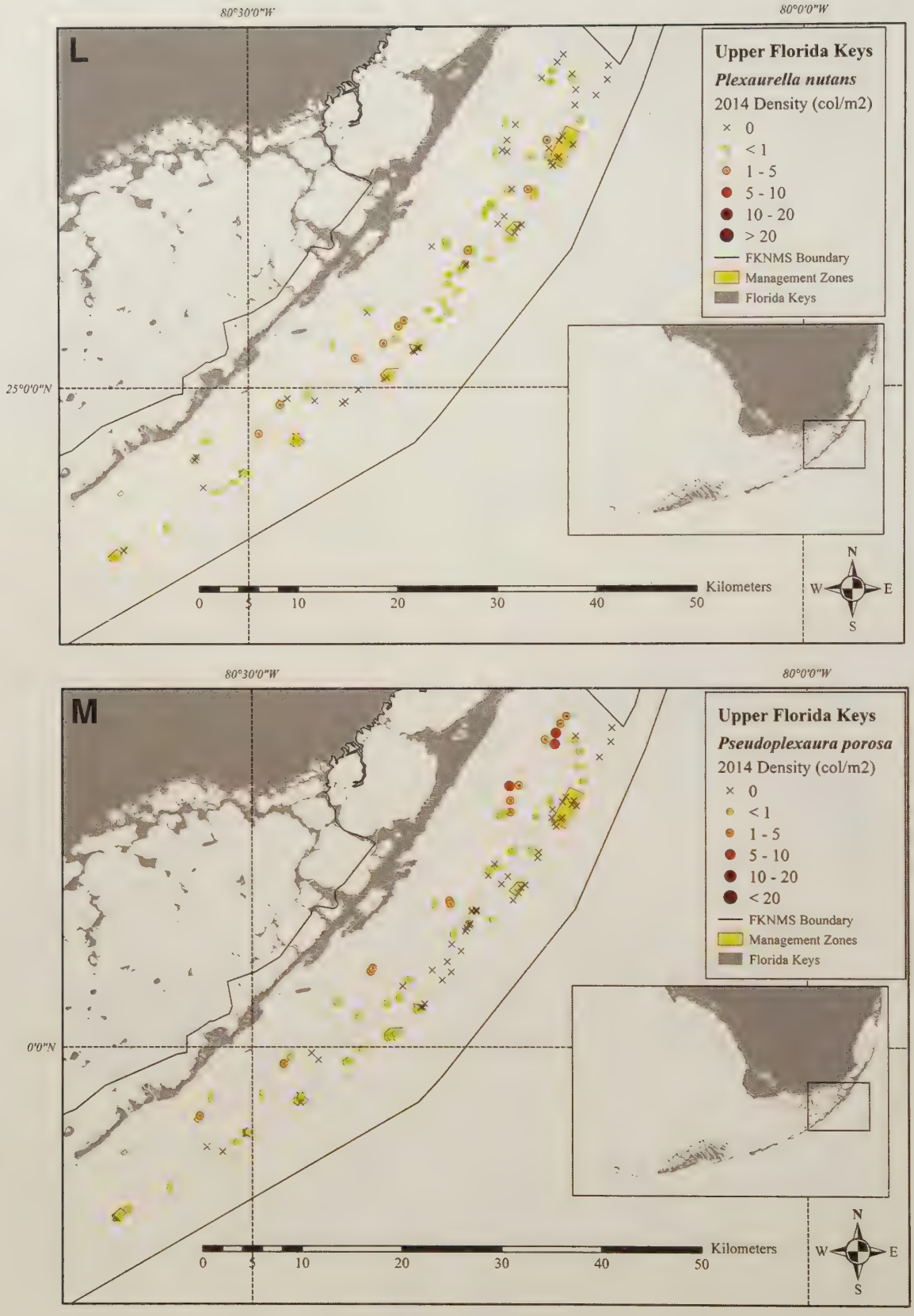

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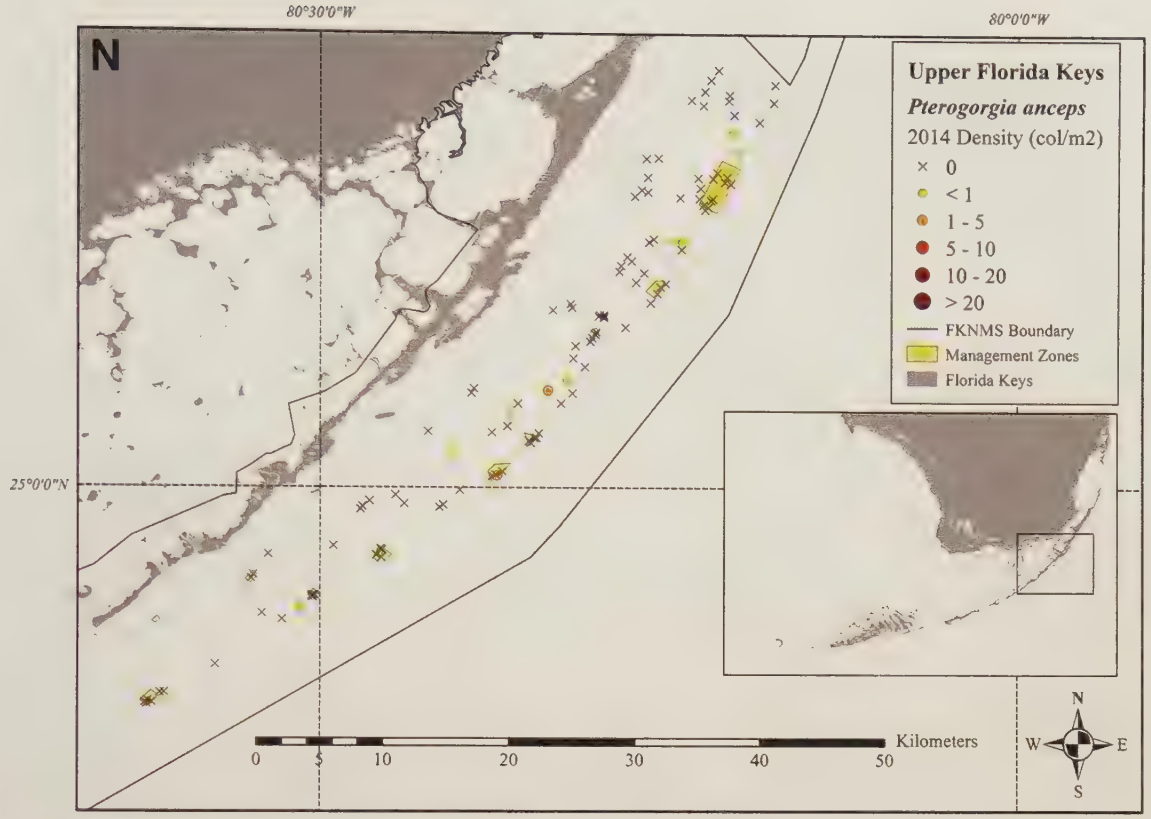

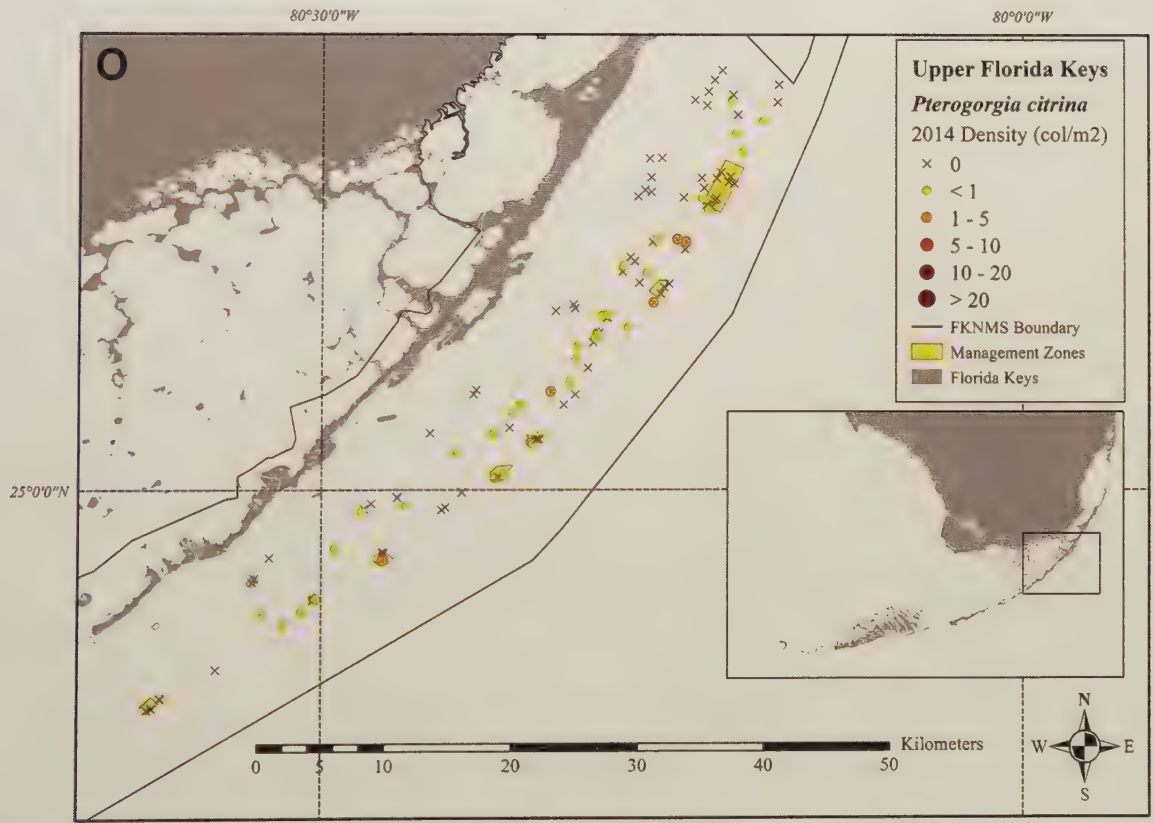

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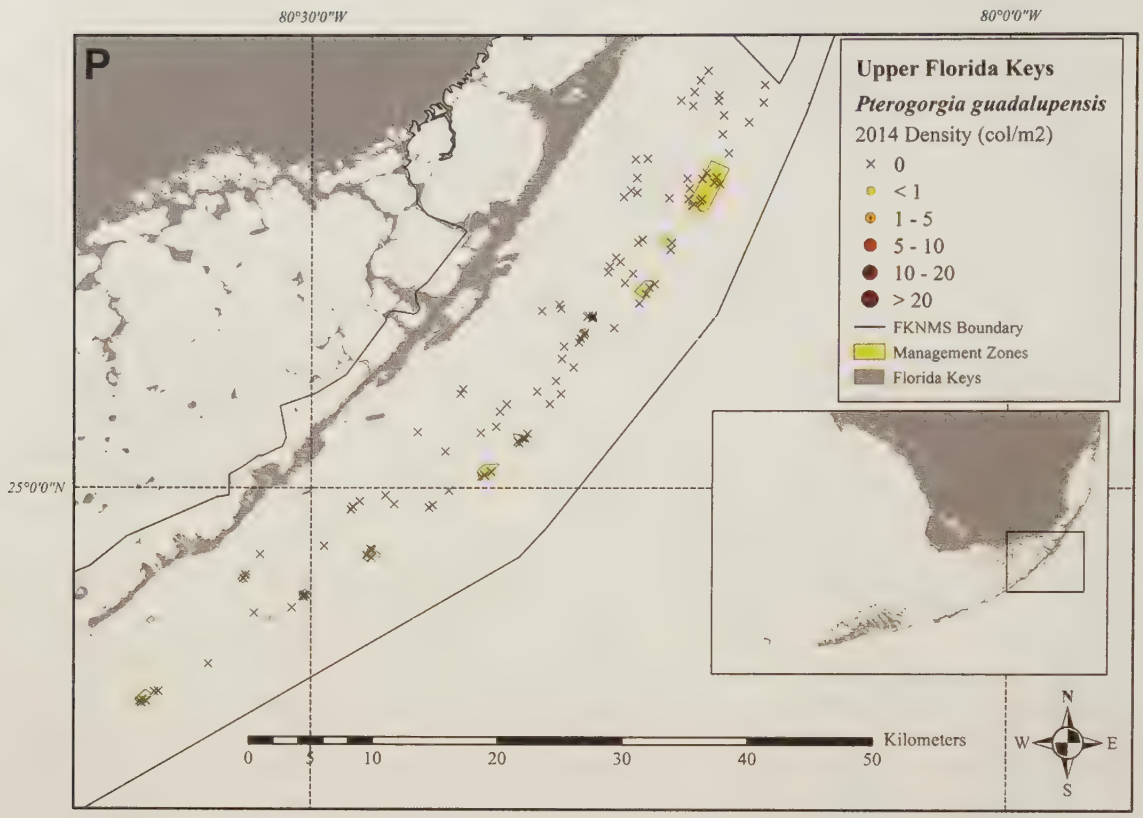

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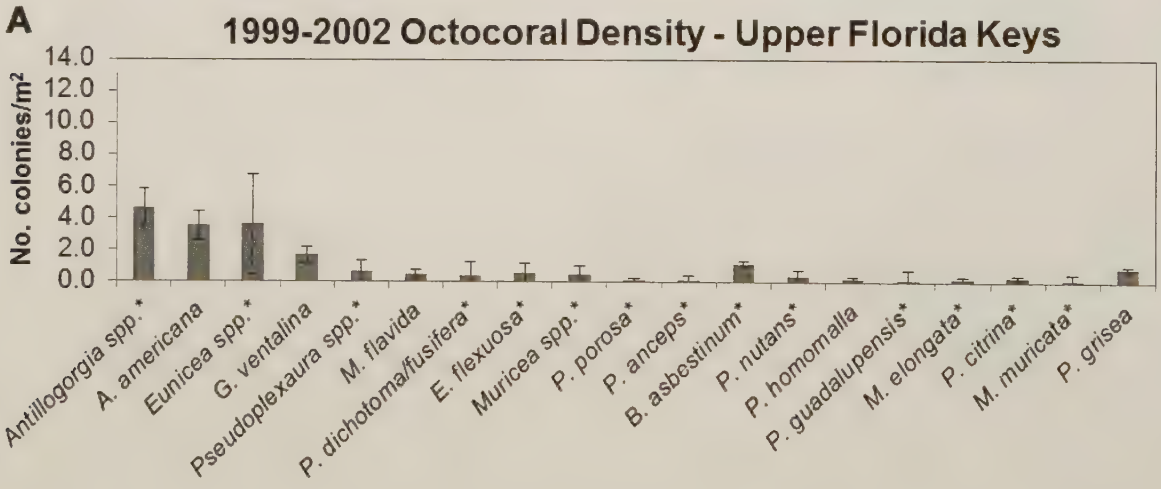

Figure 12.—Octocoral densities (in the upper Florida Keys from Carysfort Reef, northern Key Largo to Alligator Light, Upper Matecumbe Key, based upon surveys during A) 1999–2002, B) 2005, C) 2009, and D) 2014. Species are ranked along the x-axis based upon 2014 densities. Error bars represent 95% confidence intervals. Octocoral species or genera targeted in the octocoral fishery are indicated with an asterisk (*).

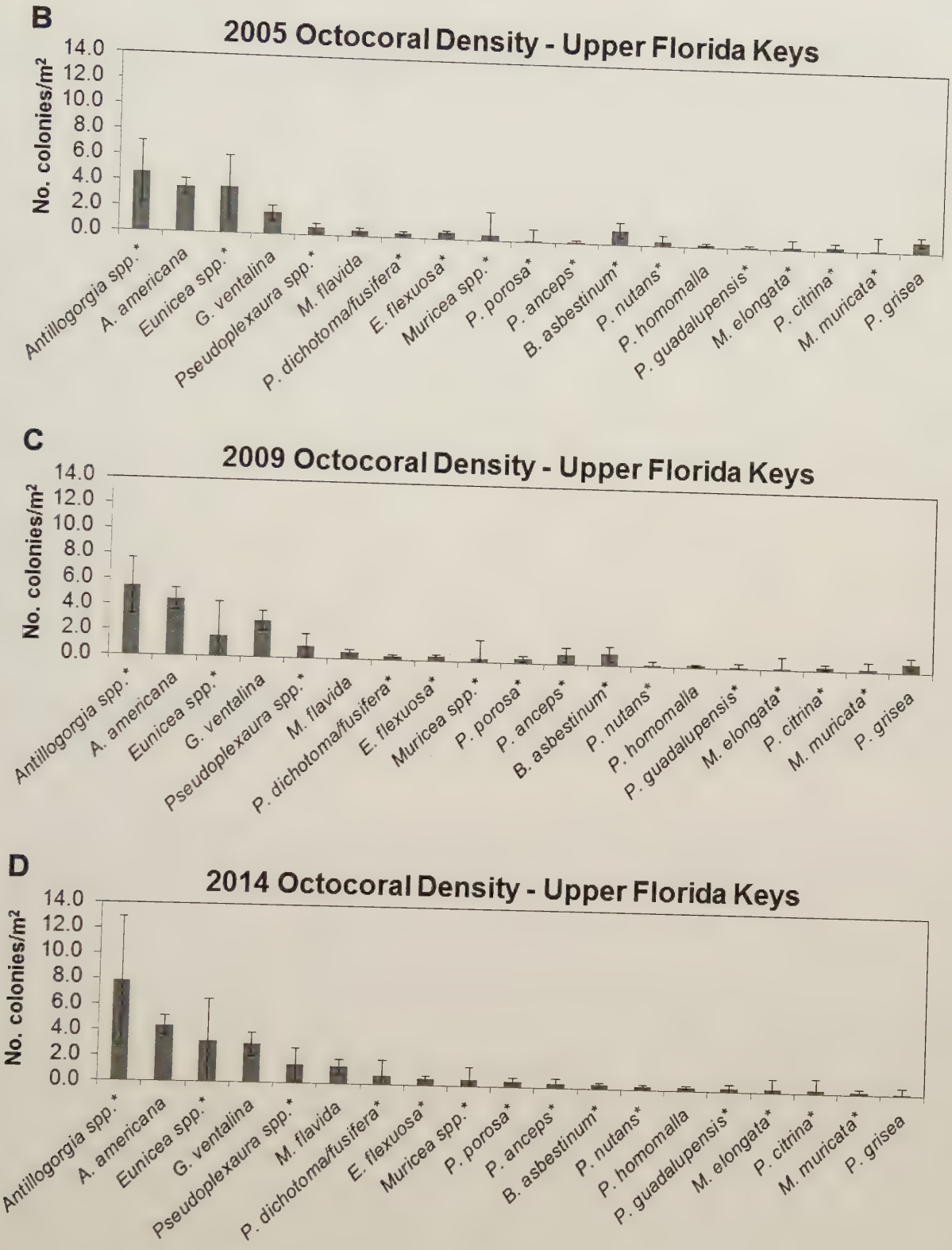

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Table 9.—Octocoral density estimates (mean no. colonies per m^2 ± 95% CI) for sampled hard-bottom and coral reef habitats in the upper Florida Keys from Carysfort Reef, northern Key Largo to Alligator Light, Upper Matecumbe Key during 1999–2014. Asterisk (*) indicate the most highly valued species or genera targeted by the octocoral fishery. Octocorals are further divided by color group (i.e., purple, red, other). nd = not encountered/no data. Note that octocorals in the red collector group (*Diodogorgia*, *Ellisella*, *Iciliogorgia*, *Leptogorgia*, *Nicella*, and *Swiftia*) were not encountered during the benthic surveys.

Octocoral taxa/collector group	1999–2002	2005	2009	2014
Other species group				
*Diodogorgia nodulifera**	nd	nd	nd	nd
Muricea spp.*[1]	1.24 ± 0.53	0.43 ± 1.80	0.29 ± 1.43	0.50 ± 1.01
M. elongata	0.33 ± 0.16	0.16 ± 0.56	0.13 ± 0.85	0.26 ± 0.85
M. muricata	0.92 ± 0.38	0.15 ± 1.00	0.16 ± 0.57	0.23 ± 0.16
M. pinnata	nd	nd	nd	nd
Plexaura homomalla	0.33 ± 0.14	0.19 ± 0.13	0.16 ± 0.11	0.29 ± 0.12
Plexaurella dichotoma/fusifera	0.25 ± 0.87	0.36 ± 0.16	0.29 ± 0.13	0.68 ± 1.24
*P. nutans**	0.28 ± 0.41	0.37 ± 0.45	0.13 ± 0.25	0.30 ± 0.13
*Pterogoria citrina**	0.23 ± 0.11	0.30 ± 0.26	0.28 ± 0.20	0.25 ± 0.86
Total density (other)	2.33 ± 2.06	1.65 ± 2.81	1.14 ± 2.12	2.02 ± 3.36
Purple species group				
Antillogorgia spp.*[2]	3.05 ± 1.21	4.64 ± 2.42	5.41 ± 2.21	7.86 ± 5.01
*Briareum asbestinum**	0.29 ± 0.17	1.14 ± 0.58	0.93 ± 0.57	0.33 ± 0.13
Eunicea spp.[3]	2.30 ± 3.16	3.59 ± 2.49	1.58 ± 2.72	3.22 ± 3.29
*E. flexuosa**	0.29 ± 0.59	0.53 ± 0.16	0.35 ± 0.12	0.54 ± 0.16
*Muriceopsis flavida**	0.39 ± 0.26	0.45 ± 0.23	0.53 ± 0.21	1.33 ± 0.60
Pseudoplexaura spp.[4]	0.93 ± 0.74	0.59 ± 0.35	0.98 ± 0.89	1.44 ± 1.30
P. porosa	0.13 ± 0.14	0.12 ± 0.90	0.33 ± 0.25	0.48 ± 0.23
*Pterogorgia anceps**	0.28 ± 0.32	0.12 ± 0.11	0.75 ± 0.58	0.36 ± 0.42
P. guadalupensis	0.66 ± 0.60	0.13 ± 0.11	0.13 ± 0.25	0.27 ± 0.32
Total density (purple)	8.32 ± 7.19	11.32 ± 7.36	10.97 ± 7.79	15.82 ± 11.47
Not targeted				
A. americana	3.97 ± 0.92	3.52 ± 0.61	4.42 ± 0.88	4.40 ± 0.73
Gorgonia ventalina	1.78 ± 0.49	1.67 ± 0.57	2.87 ± 0.80	2.99 ± 0.89
P. kuna[4]	nd	0.32 ± 0.55	0.14 ± 0.11	0.65 ± 0.60
P. grisea	0.32 ± 0.13	0.85 ± 0.40	0.68 ± 0.46	0.12 ± 0.47
Total density (not targeted)	6.07 ± 1.53	6.37 ± 2.13	8.10 ± 2.25	8.16 ± 2.69
Total octocoral density (all groups)	16.72 ± 10.79	19.33 ± 12.29	20.22 ± 12.17	26.00 ± 17.52

[1]Includes the taxa *M. elongata*, *M. laxa*, and *M. muricata*
[2]Includes the taxa *A. acerosa*, *A. bipinnata*, *A. elisabethae*, *A. kallos*, and *A. rigida*. Although *A. acerosa* can be yellow-golden in color and is included in both the purple and other categories, > 99% of colonies encountered are purple and are thus included in the purple category.
[3]Includes the taxa *E. calyculata*, *E. fusca*, *E. knighti*, *E. mammosa*, *E. palmeri*, *E. succinea* and *E. tourneforti*
[4]Includes the taxa *P. flagellosa*, *P. wagenaari*, and unidentifiable *Pseudoplexaura* colonies
[5]*Plexaura kuna* was not distinguished from *Eunicea flexuosa*, then known as *Plexaura flexuosa*, during 1999-2002.

octocoral species, comparing the top ten densest species in the upper Florida Keys, remained mostly unchanged (Fig. 12).

Florida Keys Population Abundance Estimates

Estimates of octocoral abundance for the upper Florida Keys are illustrated in Figure 13 and Table 10. Population abundance estimates are based upon colony densities and habitat area and demonstrate the large population sizes (tens to hundreds of millions of colonies) for most gorgonian taxa. Total colony abundances in the upper Florida Keys either suggest non-significant changes over time or increases (Table 10). The relative abundance of octocoral species, comparing the top ten densest species in the upper Florida Keys, is mostly unchanged based upon surveys in 1999–2002, 2005, 2009, and 2014 (Fig. 13). Table 11 lists octocoral abundance estimates for the Florida Keys, excluding the Marquesas and Dry Tortugas, from 1999–2009, which are referenced below to help evaluate the impact of octocoral fishery landings from FWC trip ticket data relative to estimated population sizes.

Fishery Information Needs and Management Recommendations

Assessment of Identification Aides

General knowledge about octocorals targeted in the marine life trade is probably sufficient to address many of the fundamental questions related to species identifications, life history, and population abundance. Bayer (1961) published one of the first octocoral identification guides for the western Atlantic that included an illustrated key to over 100 species within four orders: Telestacea, Alcyonacea, Gorgonacea, and Pennatulacea. In 1977, Cairns (1977) published a follow-up identification guide of common octocorals that included photographs of dried colonies from Florida, the Caribbean, and Gulf of Mexico. Sánchez and Wirshing (2005) improved upon these and other earlier works, with their field guide to zooxanthellate octocorals in the western Atlantic. High-resolution in-situ photographs and flow charts based on basic morphological characters were meant to be used as a quick field reference for identification. In 2011, Dr. C. Messing of Nova Southeastern University (NSU) spearheaded a workshop to develop an online interactive guide to South Florida octocorals funded as part of this overall octocoral fishery investigation. With assistance from leading octocoral experts, samples that had been photographed in-situ, and then preserved, were positively identified using microscopic examination of sclerites. Large dried colonies from the NSU invertebrate collection were also photographed. The major outcome of the workshop was a web-based octocoral guide (www.cnso.nova.edu/ncri/sofla_octocoral_guide/index.html/). Users can search through a list of octocoral species or click through character menus related to growth form, color, or aperture shape to narrow species searches. Once a species is selected, a page is linked that includes information on its habitat and ecology, along with photographs. Currently, the South Florida octocoral identification guide includes 47 species. The guide, plus other taxonomic records, were used to help inform the production of a fishery-specific identification guide that was developed as part of this octocoral fishery project.

To supplement the online interactive South Florida octocoral guide described above, a waterproof field guide has been suggested as a potentially useful tool for octocoral collec-

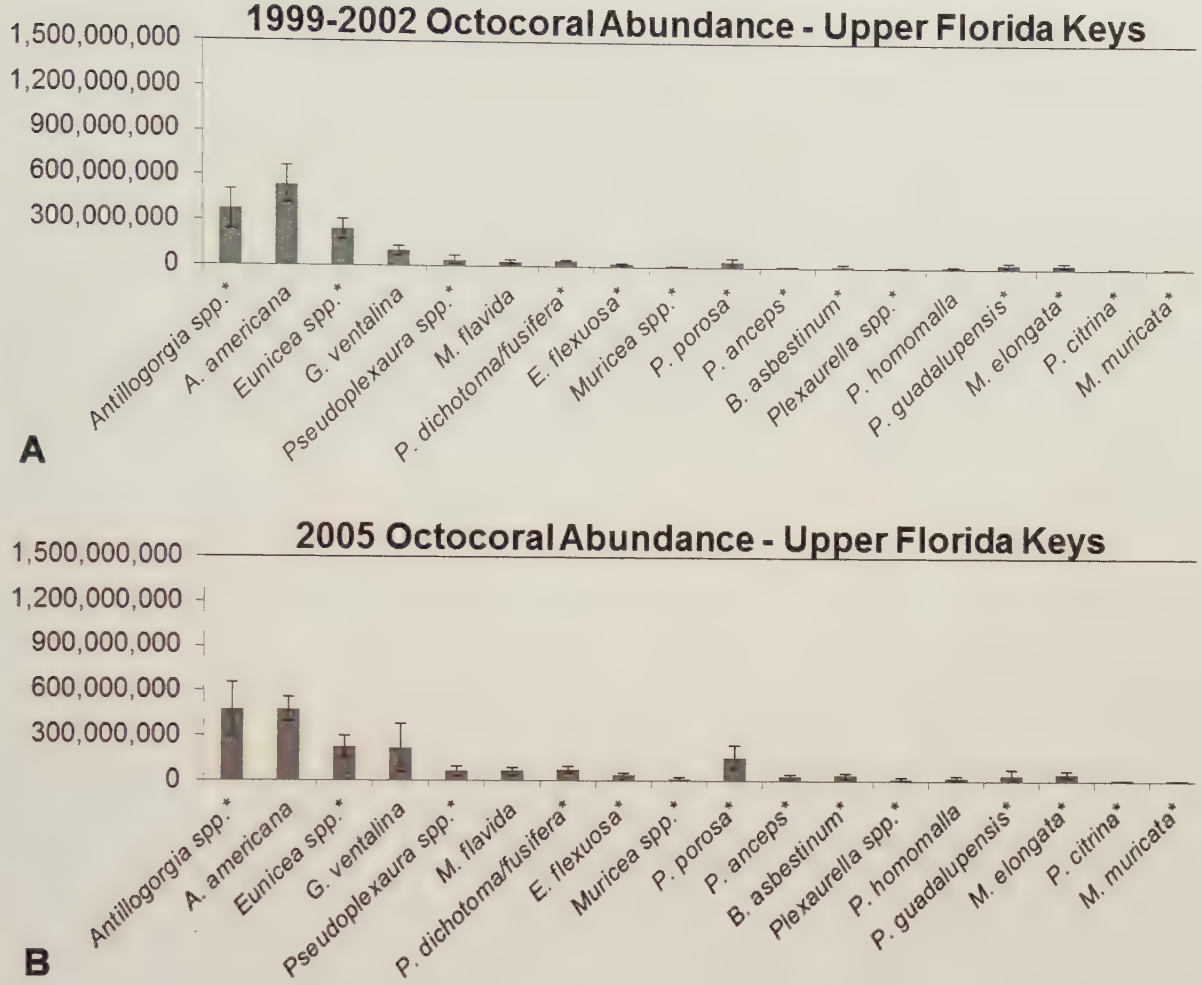

Figure 13.—Octocoral abundance (total colonies) in the upper Florida Keys from Carysfort Reef, northern Key Largo to Alligator Light, Upper Matecumbe Key, based upon surveys during A) 1999–2002, B) 2005, C) 2009, and D) 2014. Species are ranked along the x-axis from high-to-low based upon 2014 abundances. Error bars represent 95% confidence intervals. Octocoral species or genera targeted in the octocoral fishery are indicated with an asterisk (*).
Figure 13 continues on next page.

tors, with a broader intended audience to include law enforcement, hobbyists, and the public. A guide is currently being developed that will be organized by the color headings currently used to report collection activities in the FWC Trip Ticket reports (i.e., other, purple, and red categories). Under each heading, color photographs taken in situ of the octocoral species commonly collected in the fishery will list both the scientific name and the official common name. A major discrepancy within the marine life fishery is the misuse of common names such that a single species may be known by several common names (Bayer, 1961; Voss et al., 1969; Cairns, 1977; Cairns et al., 2002). This complicates and confuses the tracking and marketing of species sold within the fishery. Furthermore, species misidentification is an ongoing problem for both the fishery and scientific communities. A goal of the field guide is to provide a tool that can be used by all participants within the marine life fishery (e.g., collector, wholesaler, hobbyist, and law enforcement) to help create consistency with the identification and naming of octocorals. To assist in identification, basic habitats where octocoral species occur, collection depths, and distinguishing diagnostic characteristics will be noted for each species. Figure 14 presents a draft page from the field guide. If ongoing interest exists, workshops could be held to assist collectors in the use of these guides.

Life History Traits

There is nothing unusual or notable about octocoral life histories that suggest that the current level of collection, based upon collector interviews,

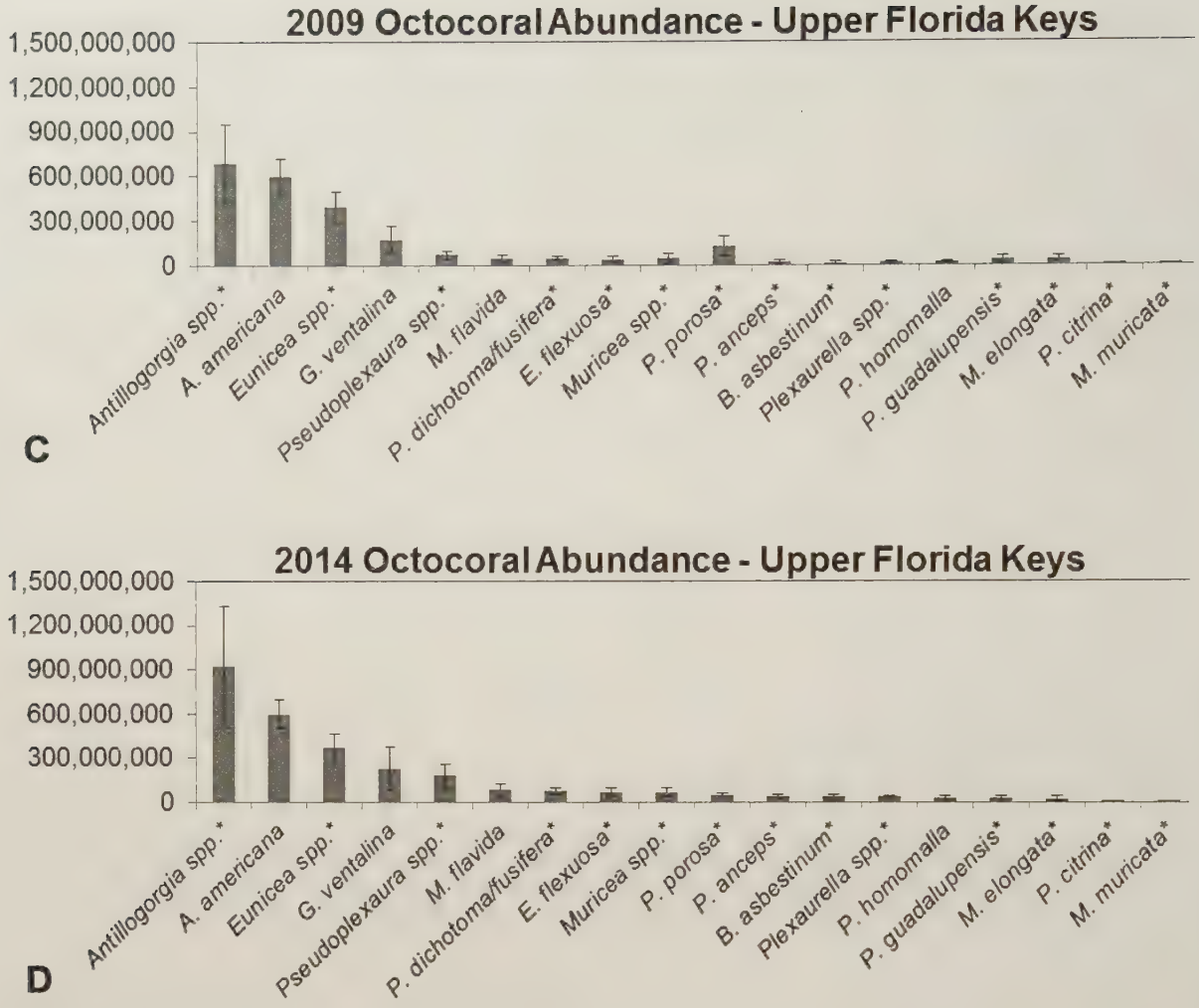

Figure 13.—*Continued.*

FWC trip ticket data, and available fishery independent assessments, is a threat to the sustainability of octocoral populations. The majority of wider Caribbean octocorals reproduce sexually, with male and female colonies that are distinct. There is no indication that octocoral collectors selectively target colonies based upon gender. Many species also reproduce asexually through fragmentation and vegetative propagation, supporting high population growth rates (Lasker, 1988; Kahng et al., 2011). Many octocoral colonies spawn over several days over consecutive months in a year (Fitzsimmons-Sosa et al., 2004; Gutierrez-Rodriguez and Lasker, 2004). Of the octocoral species collected for the aquarium trade (23 species and 15 genera), reproductive mode and timing of reproduction is known for 12 species. The majority of these (10 of 12 species) are broadcast spawners that release gametes during the summer months. *Antillogorgia elisabethae* and *Muriceopsis flavida*, on the other hand, release gametes during the winter months (Kahng et al., 2011). Brooding species, where males release gametes that fertilize eggs retained by females, include *A. elisabethae*, *Briareum asbestinum*, *Muriceopsis flavida*, and *Pterogorgia anceps* (Ritson-Williams, 2010; Kahng et al., 2011). The planula of brooders, which form from the fertilized egg and have cilia or hair-like projections that aid in movement, settle immediately after detaching from the parental colony (Brazeau and Lasker, 1990). This is significant because brooding colonies can contribute directly to the population dynamics of the immediate reef area. If substantial quantities of adult colonies of any of these brooding species were removed from a single area, similar to forest clear-cutting, then one would expect a significant decrease in reproductive output (Goffredo and Lasker, 2008). The collectors interviewed for this report stated that clear-cutting for octocorals is not practiced.

Octocorals generally grow faster than most stony corals, with linear branch extensions of 4 cm/yr in thinly branched species of *Antillogorgia*,

Purple Octocorals
Eunicea flexuosa
Bent Sea Rod
Muriceopsis flavida
Rough Sea Plume
Antillogorgia acerosa
Sea Plume
Briarium asbestinum
Corky Sea Finger
Habitat: All types of reefs and rocky-coral environments
Depth: to 50 m
Appearance: Candelabrum shape with many short branches and small polyps
Habitat: Primarily patch reefs
Depth: to 30m
Appearance: Round branchlets that grow around center branch similar to needles of a pine tree
Habitat: shallow and spur and groove reefs
Depth: to 30m
Appearance: Deep purple, colonies are bushy with many branches, branchlets are flat, somewhat thick, and widely spaced
Habitat: Back reef areas, coral rubble, sea grass beds
Depth: to 30m
Appearance: Vertical, cylindrical "fingers" with large polyps giving it a hairy appearance

Figure 14.—Draft page for the Octocoral Field Identification Guide.

Muricea, and *Muriceopsis*. However, thicker branched species such as *Plexaurella* barely grow 1 cm/yr (Yoshioka and Yoshioka, 1991). Faster-growing species tend to be found at higher densities (Yoshioka, 1997). Octocorals typically reach sexual maturity when they are over 20 cm in height. An exception is *Pterogorgia citrina,* a small bushy octocoral that rarely grows above 30 cm in height that may reach sexual maturity sooner; however, little is known about this species. To provide adequately sized octocorals to home aquarists, collectors usually take colonies < 20 cm in height. In doing so, they leave larger colonies behind that are the major contributors of gametes to the population (Beiring and Lasker, 2000). The octocoral collectors interviewed indicated that they rotate collection sites and are selective in which colonies they collect. As aesthetics is a major factor in marketability of octocoral colonies, many 'imperfect' colonies are passed over by collectors.

In the Bahamas, colonies of *Antillogorgia elisabethae* are clipped and collected for the cosmetics industry. The bioactive compound pseudopterosin found in this species is an anti-inflammatory agent that is added to cosmetic products (Look et al., 1986). Colonies of *A. elisabethae* are collected by cropping colonies that are 5–15 cm in height and collectors rotate sites on a 2–3 yr basis to allow recovery before re-collecting. Castanaro and Lasker (2003) measured accelerated growth rates among collected colonies, particularly those that retained at least 12 branches in size. However, because collected colonies are smaller, fewer zygotes are produced, reducing recruitment at collection sites. As a result, collectors have switched to collecting at 5-yr intervals to give colonies greater time to reproduce before the next collection (Goffredo and Lasker, 2008). Octocoral collectors in Florida who clip 20-cm fragments from adult colonies for Eco-Gorgs® leave behind over 80% of the colony. The impact on reproduction is probably minimal to individual colonies and insignificant to the larger population because only a small fraction of the larger population is clipped for fragments, but this requires additional study to confirm.

Information Gaps in Life History

Though some species of octocorals are relatively well-studied (e.g., *Antillogorgia* spp., *Eunicea flexuosa*, *Gorgonia ventalina*, *Plexaura kuna*, *P. homomalla*), gaps in life history data exist for several targeted genera and species. Besides distribution data and one study on reproduction (Ritson-Williams, 2010), for example, the only well-studied aspect of the genus *Pterogorgia* are the secondary metabolites found within its tissues (Schmitz and Lorance, 1971; Lorance, 1977; Pawlik and Fenical, 1992; Rodriguez and Ramirez, 1994; Jensen et al., 1996). A brief observation in October 2009 of surface brooding in colonies of *P. anceps* in Belize was noted by Ritson-Williams (2010). This paucity of life history data is somewhat unusual for a common, easily identifiable, shallow-water genus. As noted above, surveys focusing on size and mode of reproduction would be relevant in *Pterogorgia* to determine how size and morphology are related to reproductive output. However, this interest might be largely academic, because there is no evidence to suggest that population numbers are being adversely impacted at current collection levels in the U.S. South Atlantic. There is also a paucity of life history information on octocorals of the genus *Muricea*; only information on the breeding period of *M. atlantica* (gametes are present June–September) is available (Fitzsimmons and Hallock Mueller, 1996). Even though it is a commonly requested octocoral for the aquarium trade, additional studies are not considered a priority because existing population numbers appear to be large enough in relation to current collection levels.

Studies of octocorals at deeper (30+ m) depths (e.g., *Diodogorgia nodulifera* and *Swiftia exserta*) have primarily described their presence or absence at various locations throughout the wider Caribbean (Bayer, 1961; Veronique, 1987; Humann, 1993). Density data for these two deepwater species are not available from the literature. Anecdotally, information from collectors suggests that these species are found in high densities in Palm Beach County, with colonies spaced a few centimeters apart, and at relatively high colony densities in Miami–Dade County, with

Table 10.—Octocoral abundance estimates (total colonies ± 95% CI) in sampled hard-bottom and coral reef habitats in the upper Florida Keys from Carysfort Reef, northern Key Largo to Alligator Light, Upper Matecumbe Key during 1999–2014. Asterisks (*) indicate the most highly valued octocoral species or genera targeted by the fishery. Octocorals are further divided by color group (i.e. purple, red, and other). nd = no data. Note that octocorals in the red collector group (e.g. *Diodogorgia, Ellisella, Iciliogorgia, Leptogorgia, Nicella,* and *Swiftia*) were not encountered during the upper Florida Keys benthic surveys.

Octocoral taxa/collector group	1999-2002	2005	2009	2014
Other species group				
*Diodogorgia nodulifera**	nd	nd	nd	nd
Muricea spp.*[1]	16,797,660 ± 7,211,207	34,960,192 ± 20,322,052	39,246,900 ± 19,373,360	67,777,312 ± 25,963,333
M. elongata	4,359,698 ± 2,111,128	14,376,154 ± 7,629,469	17,839,500 ± 11,605,665	35,989,570 ± 11,493,995
M. muricata	12,437,962 ± 5,100,079	20,420,673 ± 12,368,587	21,407,400 ± 7,767,695	31,787,742 ± 14,469,338
M. pinnata	nd	nd	nd	nd
Plexaura homomalla	4,487,925 ± 1,945,163	25,811,731 ± 18,330,061	21,917,100 ± 15,532,634	38,912,581 ± 16,817,943
Plexaurella spp.*	28,209,811 ± 12,326,630	49,826,442 ± 22,861,624	39,586,700 ± 18,595,991	64,397,581 ± 33,864,573
*Pterogorgia citrina**	30,902,566 ± 15,140,642	39,534,423 ± 35,182,956	37,887,700 ± 26,772,620	27,859,946 ± 11,742,691
Total abundance (other)	80,397,962 ± 36,623,642	150,132,788 ± 96,696,692	138,638,400 ± 80,274,605	198,947,419 ± 88,388,542
Purple species group				
Antillogorgia spp.*[2]	374,677,585 ± 132,298,971	478,170,481 ± 176,419,729	688,264,900 ± 258,903,714	923,580,054 ± 412,160,297
*Briareum asbestinum**	39,237,283 ± 23,377,355	155,197,115 ± 79,368,560	125,726,000 ± 68,905,724	44,758,602 ± 18,241,600
Eunicea spp.[3]	99,631,925 ± 33,934,826	219,399,712 ± 157,299,336	170,579,600 ± 96,285,956	227,355,430 ± 149,445,948
*E. flexuosa**	38,980,830 ± 8,071,085	72,207,500 ± 22,209,603	47,062,300 ± 15,861,707	73,166,613 ± 21,973,470
*Muriceopsis flavida**	40,904,226 ± 27,271,051	61,752,115 ± 30,872,926	71,358,000 ± 28,896,058	181,226,667 ± 80,268,316
Pseudoplexaura spp.[4]	12,694,415 ± 8,835,166	34,960,192 ± 20,849,658	13,252,200 ± 12,104,263	36,811,667 ± 17,624,464
P. porosa	1,795,170 ± 1,406,924	15,029,615 ± 12,218,382	45,023,500 ± 34,347,016	65,859,086 ± 31,928,218
*Pterogorgia anceps**	384,679 ± 431,954	1,633,654 ± 1,529,584	1,019,400 ± 783,155	4,841,237 ± 5,711,015
P. guadalupensis	897,585 ± 815,207	1,797,019 ± 1,550,504	169,900 ± 337,117	365,376 ± 437,514
Total abundance (purple)	609,203,698 ± 236,442,539	1,040,147,404 ± 502,318,282	1,162,455,800 ± 516,424,711	1,557,964,731 ± 737,790,843
Not targeted				
A. americana	539,192,075 ± 125,201,041	478,170,481 ± 82,948,559	600,766,400 ± 119,118,372	597,573,011 ± 95,566,345
Gorgonia ventalina	241,835,019 ± 66,173,864	227,241,250 ± 77,682,730	390,090,400 ± 107,499,242	370,948,333 ± 96,755,309
P. kuna[4]	nd	4,410,865 ± 7,415,976	1,868,900 ± 1,541,617	822,098 ± 813,253
P. grisea	4,103,245 ± 1,712,921	10,945,481 ± 5,411,117	9,174,600 ± 1,541,617	16,715,968 ±x 813,253
Total abundance (not targeted)	785,130,340 ± 193,087,825	720,768,077 ± 193,087,825	1,001,900,300 ± 234,466,637	986,059,409 ± 199,487,414
Total octocoral abundance (all groups)	1,474,732,000 ± 466,154,007	1,911,048,269 ± 772,473,357	2,302,994,500 ± 831,165,953	2,742,971,559 ± 831,165,953

[1]Includes the taxa *M. elongata*, *M. laxa*, and *M. muricata*
[2]Includes the taxa *A. acerosa*, *A. bipinnata*, *A. elisabethae*, *A. kallos*, and *A. rigida*. Although *A. acerosa* can be yellow-golden in color and is included in both the purple and other collector categories, > 99% of colonies encountered are purple and are thus included in the purple category.
[3]Includes the taxa *E. calyculata*, *E. fusca*, *E. knighti*, *E. mammosa*, *E. palmeri*, *E. succinea* and *E. tourneforti*
[4]Includes the taxa *P. flagellosa*, *P. wagenaari*, and unidentifiable *Pseudoplexaura* colonies
[5]*Plexaura kuna* was not distinguished from *Eunicea flexuosa*, then known as *Plexaura flexuosa*, during 1999-2002.

colonies generally 7 m apart. Several hundred colonies can be collected in a single dive. Populations of these two species may serve as important habitat for other marine life, but little information exists. Studies of *S. exserta* have focused on their associated microbiota (Bruck et al., 2007), morphology (Menzel et al., 2012), and biology (Olano and Bigger, 2000). Interestingly, collectors have observed morphological differences between *S. exserta* colonies in Palm Beach County, where colonies are short and rigid, with those in Miami–Dade County, where colonies are tall and flexible. Growth and regeneration rates of *S. exserta* would be interesting to obtain related to collection methods (e.g., fragmentation for Eco-Gorgs®), but there is no evidence that current collection levels are negatively affecting populations of these two species.

Population Abundance Estimates

Benthic surveys for octocorals conducted in the Florida Keys during the past 15 years provide habitat-specific density and population abundance estimates. Time series data from 1999–2014 for octocoral taxa are available for the upper Florida Keys, representing the longest time series available for density (Fig. 12, Table 9) and abundance data (Fig. 13, Table 10). Total abundance for collected species in the Florida Keys is presented for 2009, the most recent sampling that included the entire Florida Keys from northern Biscayne National Park to southwest of Key West (Table 11). The surveys were conducted as part of a Florida Keys-wide monitoring and assessment program designed to evaluate benthic community structure nearshore to offshore, among different habitat types, and inside and outside of marine protected areas (Miller et al., 2002; Smith et. al., 2011). However, many nearshore locations used by marine life collectors, such as tidal channels, bridge pilings, and Florida Bay or Biscayne Bay octocoral patches, were not sampled as part of this program. Among the 47 species recorded in the Keys-wide surveys, population densities and abundances are presented for 15 species (Fig. 11) that represent those collected in the octocoral fishery (Table 12). Species are also divided for comparison into the "other, purple, and red" groups reported by collectors. Species from the "red" group are found at depths outside of the range targeted in Florida Keys-wide benthic surveys (< 15 m depth), so data are unavailable for these species.

In the upper Florida Keys, total octocoral population numbers for both "other" and "purple" groups have increased significantly during the last 15 years (Table 10), from over 80 million colonies in 1999–2002 (combined) to almost 200 million in 2014 for octocorals in the "other," category, and from over 600 million to more than 1.5 billion in 2014 for octocorals in the "purple category." In 2009 in the upper Florida Keys, totals for the "other" and "purple" categories were approximately 140,000 and just over 1.4 billion, respectively. Total numbers for colonies Florida Keys-wide in 2009 for "other" and "purple" was estimated at just over 500 million and nearly 2 billion colonies, respectively (Table 11). While the threshold number of 70,000 colonies allowed for collecting has never been exceeded, this threshold represents 0.004% of total octocoral numbers for collected species as determined in 2009. The actual number of colonies reported by collectors in 2009 was 16,053 for "other" and 19,228 for "purple." When compared to the total numbers of octocorals in the natural population for each group, the percentages are 0.003% and 0.001%, respectively for "other" and "purple" categories (Fig. 13). Population estimates at the individual species level are potentially more relevant to management interests, but these group estimates provide a first-order assessment that documents the large number of octocorals in the Florida Keys and the relatively miniscule numbers collected in the octocoral fishery. Since genera or species level data are not reported by collectors, estimates of relative percentages collected by species are not explicitly possible, although there is now a better understanding of the species collected in each species color group (Table 2).

For the "red" species found in deeper water (> 20 m depth), anecdotal evidence from collectors indicates that large patches of *Diodogorgia nodulifera* and *Swiftia exserta* exist in Palm Beach County at depths of 18–45 m and in Miami-Dade County at 25–30 m. The patches are apparently dense and persistent. One collector reported that he returns to the same general area several times per year and easily find hundreds of colonies on a single dive. In fact, surveys along much of the southeastern coast of the United States indicate that *S. exserta* is broadly distributed along the edge of the continental shelf, and deeper. Although limited information is available from the literature on deeper water oc-

Table 11.—Octocoral abundance estimates (total colonies ± 95% CI) for sampled hard-bottom and coral reef habitats from northern Biscayne National Park to east of the Marquesas Keys, Florida Keys, during 1999–2009. The most highly valued octocoral species or genera targeted are indicated with an asterisk (*) and are further divided by color group (i.e. purple, red, and other). nd = no data. Note that octocorals in the red collector group (e.g. *Diodogorgia*, *Ellisella*, *Iciligorgia*, *Leptogorgia*, *Nicella*, and *Swiftia*) were not encountered during these surveys.

Octocoral taxa/collector group	1999-2002	2005	2009
Other species group			
*Diodogorgia nodulifera**	nd	nd	nd
Muricea spp.*[1]	114,466,278 ± 23,345,596	229,332,813 ± 44,812,261	270,783,127 ± 54,530,487
M. elongate	54,896,155 ± 13,416,666	129,844,550 ± 23,802,005	149,545,171 ± 30,493,430
M. muricata	59,403,547 ± 10,601,445	98,981,708 ± 20,419,537	121,237,956 ± 24,037,057
M. pinnata	nd	nd	nd
Plexaura homomalla	51,131,235 ± 13,974,304	90,685,145 ± 24,536,639	71,650,109 ± 23,179,909
Plexaurella spp.*	91,941,210 ± 22,984,308	133,700,718 ± 35,218,576	61,457,283 ± 28,670,931
*Pterogorgia citrina**	47,353,292 ± 16,364,273	58,926,251 ± 36,218,576	61,457,283 ± 28,670,931
Total abundance (other)	304,892,015 ± 77,668,481	512,644,926 ± 140,749,768	502,066,548 ± 130,939,795
Purple species group			
Antillogorgia spp.*[2]	531,244,061 ± 145,690,832	717,169,257 ± 188,139,742	834,535,525 ± 274,982,791
*Briareum asbestinum**	76,833,389 ± 28,820,534	256,057,667 ± 91,398,237	202,025,444 ± 77,658,165
Eunicea spp.[3]	389,162,980 ± 81,019,210	547,578,643 ± 198,535,609	416,116,429 ± 124,077,575
*E. flexuosa**	185,228,376 ± 23,125,728	266,279,655 ± 40,101,745	190,583,527 ± 35,674,286
*Muriceopsis flavida**	62,159,541 ± 27,764,515	91,947,753 ± 31,754,005	91,947,753 ± 32,270,055
Pseudoplexaura spp.[4]	69,971,429 ± 25,084,018	179,075,503 ± 36,586,142	35,070,418 ± 14,600,796
P. porosa	51,464,030 ± 16,649,265	81,975,495 ± 24,831,817	155,932,898 ± 51,472,259
*Pterogorgia anceps**	2,954,689 ± 1,725,127	2,801,050 ± 2,158,399	1,964,400 ± 1,092,191
P. guadalupensis	20,421,201 ± 35,917,649	4,565,968 ± 2,816,245	1,247,261 ± 824,147
Total abundance (purple)	1,389,439,696 ± 385,796,878	2,147,450,990 ± 616,321,940	2,147,450,990 ± 612,652,265
Not targeted			
A. americana	1,112,059,940 ± 147,609,769	1,137,085,998 ± 141,090,463	1,392,367,210 ± 154,299,778
Gorgonia ventalina	437,122,788 ± 75,248,774	472,620,974 ± 89,265,986	679,304,335 ± 118,314,731
P. kuna[4]	nd	5,501,538 ± 7,493,196	2,469,016 ± 1,651,251
P. grisea	17,072,178 ± 3,994,974	34,026,481 ± 8,087,015	20,671,706 ± 7,161,260
Total abundance (not targeted)	1,566,254,906 ± 226,853,517	1,649,234,991 ± 245,936,660	2,094,812,268 ± 281,427,021
Total octocoral abundance (all groups)	2,094,812,268 ± 273,610,977	4,759,804,279 ± 377,877,699	4,896,380,423 ± 406,830,115

[1]Includes the taxa *M. elongata*, *M. laxa*, and *M. muricata*
[2]Includes the taxa *A. acerosa*, *A. bipinnata*, *A. elisabethae*, *A. kallos*, and *A. rigida*. Although *A. acerosa* can be yellow-golden in color and is included in both the purple and other collector categories, > 99% of colonies encountered are purple and are thus included in the purple category.
[3]Includes the taxa *E. calyculata*, *E. fusca*, *E. knighti*, *E. mammosa*, *E. palmeri*, *E. succinea* and *E. tourneforti*
[4]Includes the taxa *P. flagellosa*, *P. wagenaari*, and unidentifiable *Pseudoplexaura* colonies
[5]*Plexaura kuna* was not distinguished from *Eunicea flexuosa*, then known as *Plexaura flexuosa*, during 1999-2002.

Table 12.—Octocorals surveyed in fishery independent surveys that are also targeted by octocoral collectors.

Species goup	Scientific name	Collector common name
Other	*Antillogorgia acerosa*	golden plume gorgonian
	Muricea elongata	orange spiny sea rod/rusty gorgonian
	Muricea muricata	spiny sea fan
	Plexaura homomalla	black sea rod
	Plexaurella fusifera	brown tree gorgonian
	Plexaurella nutans	giant slit pore/large polyp gorgonian
	Pterogorgia citrina	yellow ribbon/yellow sea whip gorgonian
Purple	*Antillogorgia acerosa*	purple or golden willow gorgonian
	Antillogorgia elisabethae	purple frilly gorgonian
	Antillogorgia kallos	purple plume/bi-pinnate gorgonian
	Briareum asbestinum	corky sea finger/sea stalk gorgonian
	Eunicea flexuosa	purple candelabra/swollen knob candelabrum gorgonian
	Muriceopsis flavida	purple brush/bottle brush gorgonian
	Pseudoplexaura porosa	purple tree gorgonian
	Pterogorgia anceps	purple ribbon/angular sea whip gorgonian
	Pterogorgia guadalupensis	purple blade/flat-blade/grooved-blade sea whip gorgonian

tocoral taxa, Goldberg (1973) reported *D. nodulifera* comprising approximately 5% of the total colonies on the outer fore reef off Palm Beach County. *S. exserta* was observed in relatively high abundance at 30% in the same location and lower in abundance (1.25%) inshore.

While collectors are not currently required to report at the species level, population data for each of the 15 species targeted is available (Tables 10 and 11). At the species level, octocoral abundance has increased since 1999 in the upper Florida Keys for all species in the "other" group, except *Pterogorgia citrina*, which appears relatively stable over the period considered. For the "purple" group, most species have increased or remained stable. Population sizes of *Pterogorgia anceps* and *P. guadalupensis* increased between 1999 and 2005, then fell in 2009 and increased again in 2014. It is difficult to identify the causes of these fluctuations; however, natural changes in population dynamics can occur, as large colonies break or become detached because of high wave action due to storms. In addition, *B. asbestinum* is more susceptible to bleaching-related mortality.

Currently, octocoral abundance in the upper Florida Keys is dominated by *Antillogorgia* species (Fig. 12, Table 10). Three species are particularly prized by marine aquarium hobbyists due to their vibrant purple color: *A. elisabethae* (~416 million estimated colonies), *A. kallos* (~392 million colonies), and *Muriceopsis flavida* (~181 million colonies). These octocorals are abundant and grow quickly, two traits that suggest that current collection levels probably do not negatively affect these species. In contrast, all three species in the genus *Pterogorgia* (*P. citrina, P. anceps,* and *P. guadalupensis*) and *Plexaurella fusifera* are less abundant (though ranging from hundreds of thousands to tens of millions of colonies), but little is known about whether or not these species are targeted by collectors. If one or more of the *Pterogorgia* species are brooders, local collection at "hot spots" may affect reproduction and successful recruitment, as Castanaro and Lasker (2003) documented with collection of *A. elisabethae* in the Bahamas. For example, *P. citrina* has a relatively small maximum colony size, and if collectors target the larger fecund colonies or perhaps a color morph (e.g., yellow vs. purple), there may be at least a local negative effect on populations. Despite uncertainties about population estimates for some species, there is nothing in the abundance estimates to suggest that the current collection levels for octocorals is adversely affecting octocoral populations in the Florida Keys.

Fishery Management Recommendations

Information assembled for this study aimed to address management concerns about the octocoral fishery that were raised by the South Atlantic Fishery Management Council (SAFMC) in a 22 June 2010 memo to NOAA's Southeast Fishery Science Center (NMFS/SEFSC). Specifically, the SAFMC asked for an "evaluation of octocoral landings and fishery impacts" because octocoral catch data were being used to set Acceptable Biological Catch limits and Overfish limits rather than population data. An additional concern with the octocoral fishery is that a substantial amount of taxonomic uncertainty exists among collectors, wholesalers, and law enforcement. When colonies are identified and lumped by color, rather than by species, information is lost related to life-history traits or ecological function. These are factors that that could potentially affect management strategies.

A goal of this study was to provide the SAFMC and FWC with the best available information to help manage the octocoral fishery, with the least economic impact on the collectors who depend upon this resource for income. The management recommendations are summarized as follows. Based on interviews with collectors and a synthesis of FWC Trip Ticket results, the long-term stability of the octocoral fishery is not likely to significantly change, so there is therefore little concern to be had about the fishery exceeding the 70,000 colonies/yr threshold. The social dynamics of the aquarium industry to seek colorful, rare, and exotic marine species for home aquaria places octocorals on the low end of the desired list of marine life species. Although some octocoral species are vibrantly colored (e.g., *Antillogorgia acerosa*, *Muriceopsis flavida*, *Leptogorgia* spp.), they are neither rare nor exotic. Species that are collected from deeper habitats (e.g., *Swiftia exserta* and *Diodogorgia* spp.) are difficult to keep in good health in home aquaria and are marketed as appropriate for advanced aquarists, thus resulting in minimal demand. Octocorals also do not contribute ecosystem services in home aquaria, such as control and removal of algae and detritus, which also limits demand. In addition, during the last 20 years, octocoral landings have fluctuated slightly or actually decreased.

Distribution and abundance information obtained from an exhaustive literature search, along with age, growth, population and habitat data, suggests that current information is adequate to describe the populations and the octocoral fishery, making a formal stock assessment probably a low priority. The list of 12 targeted species in original scope of work for this study was expanded to 24 species based on interviews with collectors. Considerable lumping of taxa based upon colony color still occurs. Scientifically, there are genera where additional information on population status and life history information would be academically interesting (e.g., for the genera *Muricea, Pterogorgia,* and *Diodogorgia*), but based on the current state of knowledge and collecting levels, this additional information is probably a low priority for informing management needs related to species-specific, seasonal, or depth-driven regulation of annual quotas.

The collection of octocorals, below the 70,000 colony per year quota, a level that has never been reached, does not appear to adversely impact octocoral populations. For multiple sampling periods spanning over a decade, the Florida Keys abundance estimates presented for 15 species illustrate that octocoral populations are large (tens of millions to hundreds of millions, per species) and despite some fluctuations that are likely due to natural variation (along with sampling issues and taxonomic questions) are generally increasing. This result provides evidence that current and projected octocoral collection levels are acceptable (< 0.01% of estimated population sizes) and that no octocoral species is overcollected. The scaling of quotas and landings at finer taxonomic resolution may be desirable to provide further data resolution. Further, the collectors interviewed rotate their collection sites and are selective about removing individual colonies that are size-appropriate and aesthetically pleasing for the aquarium trade. As long as octocoral collection does not increase substantially (e.g., 500 to 1,000 times current levels), natural populations are probably not threatened. These results also suggest that if demand for octocorals were to increase substantially, that the 70,000 colony quota could reasonably be increased, assuming the reason for the increased demand can be rationally evaluated. For example, if demand was to increase, is it based upon one species, one group of species, or spread across all species? In addition, better understanding of collecting methods would be relevant. For example, was demand being met through Ecogorgs®, other fragmentation methods, rotating sites, or something else?

Data collected by FWC through the Trip Ticket program is adequate to understand and manage the octocoral fishery, although FWC has proposed refinements to the reporting criteria beyond the three current octocoral categories. Regional distinctions that separate Florida Keys landings from others in Atlantic Ocean waters would be beneficial for understanding what parts of the Florida Reef Tract are utilized for collecting octocorals, since management reviews are underway in Monroe, Miami-Dade, Broward, and Palm Beach Counties. Collectors who were interviewed indicated that they would like clarification in the reporting methodology for clipped fragments versus whole colonies collected. For example, should three clippings from a single colony be recorded as three colonies or one colony?

Collectors and aquarium hobbyists stated that they would welcome and use a field guide to help with octocoral identification, which would ultimately provide better taxonomic resolution for collected species. A potential benefit to collectors who report at higher taxonomic resolution would be that they could document that their collections are eco-friendly, by linking scientific results presented here that indicate collecting represents an insignificant percentage of the total population. None of these suggestions related to recording additional or better information as part of the Trip Ticket program are needed to benefit or protect the fishery itself. Instead, they might benefit the collectors by helping them to better market octocorals. Additional taxonomic resolution for the Trip Ticket program is not being proposed, as it is not necessary for ensuring sustainability of the octocoral fishery at current levels. While collectors may benefit from the additional data, voluntary participation is recommended.

Information obtained and compiled for this study suggests that additional research is not necessarily needed to better manage the octocoral fishery. While the population biology of deepwater species remains largely unknown, there is no evidence that populations are being adversely affected by the relatively low numbers of colonies collected. Octocoral collection in the Bahamas for the cosmetics industry and the artisanal jewelry trade, for example, previously prompted studies on growth and reproduction of targeted octocoral species to understand the effects of repeated and extensive clear-cutting, sometimes to the point that only holdfasts remained (Morel et al., 1996; Castanaro and Lasker, 2003; Cadena and Sanchez, 2010). In Florida, collection for the aquarium trade dramatically contrasts with that conducted by commercial collectors for the pharmaceutical industry. The selective removal of adult colonies, sub-adult colonies, or branches from adult colonies at current levels does not appear to warrant any change to the current fishery management plan for octocorals.

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Anthropogenic Noise and the Endangered Cook Inlet Beluga Whale, *Delphinapterus leucas*: Acoustic Considerations for Management

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Introduction

Cook Inlet belugas, *Delphinapterus leucas*, are a small, geographically and genetically isolated population with strong site fidelity, making them particularly vulnerable to anthropogenic impacts (Hobbs et al.[1]). This population is in danger of extinction in the foreseeable future unless factors that are impeding recovery are identified and mitigated (Hobbs et al.[1]). Their critical habitat was designated in 2011 (NOAA, 2011) and is in close proximity to the greatest concentration of Alaska's human population and the largest urban area in the state, exposing belugas to a wide variety of stressors (Rugh et al., 2010).

Belugas are predominately found in near-shore waters of Cook Inlet, adjacent to many human activities, including fishing, hunting, timber harvest, mining, shipping, dredging, renewable energy development, wastewater discharge, military operations, oil and gas development, transportation, and residential and industrial development. The Cook Inlet Beluga Recovery Plan (NMFS, 2016) considers anthropogenic noise as a serious threat to their recovery and highlights the need to better understand its sources and effects on the population. However, the diversity and occurrence of anthropogenic noise sources in Cook Inlet have not yet been described or characterized in the context of their effects on Cook Inlet beluga communication and behavior.

Underwater noise is currently being regulated for common noise sources occurring in the inlet such as seismic surveys and pile driving. Mitigation is mainly focused on close-range injury effects defined as the onset of permanent threshold shift (PTS) and temporary threshold shifts (TTS) in marine mammal hearing, following the recently updated NOAA technical guidance report (NMFS, 2018). Although behavioral harassment is also considered as part of the mitigation, a small number of takes is often allowed because of the difficulties in monitoring the extensive areas ensonified to level B harassment threshold

[1]Hobbs, R. C., K. E. W. Shelden, D. J. Vos, K. T. Goetz, and D. J. Rugh. 2006. Status review and extinction assessment of Cook Inlet beluga (*Delphinapterus leucas*). AFSC Proc. Rep. 2006-16, 74 p. (avail. online at www.afsc.noaa.gov/Publications/ProcRpt/PR%202006-16.pdf).

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ABSTRACT—Anthropogenic noise has been identified as a major threat for the recovery of the endangered Cook Inlet beluga, Delphinapterus leucas, *population, but little is known about its occurrence in critical habitat. We analyzed 8,756 h of acoustic recordings from different locations and months in Cook Inlet, Alaska, to describe anthropogenic noise, evaluate the potential for acoustic impact to Cook Inlet belugas, and provide management recommendations. Nine total sources of noise were identified: commercial ship, dredging, helicopter, jet aircraft (commercial or military non-fighter), fighter jet, propeller aircraft, outboard motor, pile driving, sub-bottom profiler, as well as four repetitive unidentified noise sources. Several noise metrics were compared across noise sources, months, and locations. A total of 6,263 anthropogenic acoustic events were detected and classified, for a total duration of 1,025 h representing 11.7% of the sound recordings analyzed. Anthropogenic noise was present in every day sampled. The natural background noise (i.e., ambient noise without anthropogenic contribution), in areas where currents and vegetative debris did cause minimal self-noise, was below 120 dBrms re. 1μPa for 94% to 100% of the time; much lower than previously reported and unsupportive of the current application of the elevated behavioral harassment threshold for non-impulsive noise of 125 dB_{rms}. Based on spectral received levels and spatial and temporal prevalence, several anthropogenic noise sources in Cook Inlet have the potential to chronically mask beluga communication and hearing in most of the locations and periods sampled for this study. Current activities (e.g., shipping, dredging) exceed behavioral harassment levels on a daily basis in a significant portion of the critical habitat. Ship noise was identified as the top priority focus for noise mitigation management actions. A high concentration of noise sources was identified in the lower region of Knik Arm. This area is recommended for further research to evaluate the potential for beluga displacement and the basis to start considering cumulative impact effects in the permitting process. The amount of detected unidentified machinery noise or unclassifiable noises highlights the need for further research in coordination with industry, in particular in areas of oil and gas production (i.e., Trading Bay) or intense shipping related activities (i.e., facilities). Finally, unpermitted activities were also detected suggesting the need for further enforcement and outreach to increase the awareness towards this endangered population of belugas and the negative consequences of underwater noise in their protected habitat.*

(120 dB[2] for non-impulsive and 160 dB for impulsive sources, NOAA, 1995). Five previous acoustic studies collected noise data and suggested that the background noise in upper Cook Inlet may often exceed 120 dB re 1 µPa (Heenehan, 2009; Blackwell and Greene[3]; URS[4]; Širović and Kendall[5], HDR[6]). These results led the NMFS to define an exception for upper Cook Inlet of 125 dB_{rms} for behavioral harassment (level B take) by non-impulsive noise instead of the standard 120 dB_{rms} limit (NMFS[7]).

Beginning in 2008 acoustic data were collected nearly continuously over five years at 10 locations in upper, middle, and lower Cook Inlet; these recordings represent the most complete currently available set of sound recordings collected in Cook Inlet. The primary objective of the Cook Inlet Beluga Acoustics (CIBA) research program was to acoustically describe the seasonal occurrence of beluga; killer whales, *Orcinus orca*; and porpoises, *Phocoena* spp. (Lammers et al., 2013; Castellote et al.[8]; Castellote et al., 2016); documenting anthropogenic noise sources was a secondary objective. Here, we describe the background noise and anthropogenic contributors identified in a subset of these data (Fig. 1, Table 1), and, in line with proposed recovery actions (NMFS, 2016), we discuss a series of recommendations in the context of potential acoustic impact to Cook Inlet belugas and their recovery.

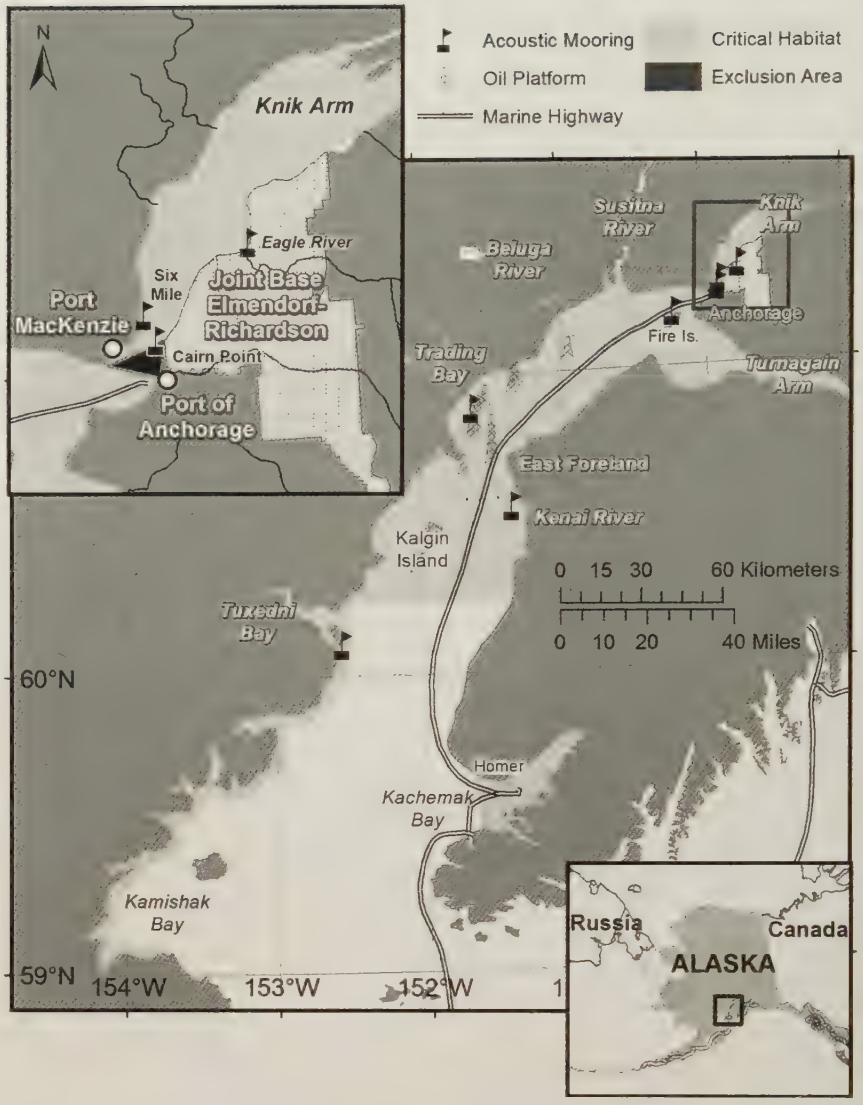


Figure 1.—Cook Inlet, Alaska, with the location of the CIBA acoustic moorings selected for this study, the Cook Inlet beluga critical habitat, main shipping routes, and oil and gas platforms.

Materials and Methods

Selection of Data Sets for Anthropogenic Noise Analysis

Overall, the sound recording methods used by the CIBA research pro-

[2]dB values are referenced to 1 µPa unless otherwise noted.

[3]Blackwell, S. B., and C. R. Greene. 2002. Acoustic measurements in Cook Inlet, Alaska, during August 2001. Rep. for Natl. Mar. Fish. Serv. Greenridge Rep. #271-1, Aug. 2002, 42 p. (avail. online at https://alaskafisheries.noaa.gov/sites/default/files/CI_Acoustics_Final.pdf).

[4]URS. 2007. Port of Anchorage Marine Terminal Development Project underwater noise survey test pile driving program, Anchorage, Alaska. Final underwater noise report. Prep. by URS for U.S. Dep. Transp. Marit. Admin. (avail. online at https://alaskafisheries.noaa.gov/sites/default/files/2007underwaternoise.pdf).

[5]Širović, A., and L. S. Kendall. 2009. Passive acoustic monitoring of Cook Inlet beluga whales. Analysis report. Prep. by AK Pacific University for Port of Anchorage. Dec. 2009, 73 p. (avail. online at www.nmfs.noaa.gov/pr/pdfs/permits/poa_acoustic_report.pdf).

[6]HDR. 2011. Ambient noise measurements near the proposed Knik Arm Crossing Site during May and July 2010. Prep. by HDR Alaska Inc. for Knik Arm Bridge and Toll Authority, Anchorage, Feb. 2011, 63 p. (on file at Alaska Dep. Transport. Pub. Facil., Anchorage).

[7]NMFS. 2009. Endangered Species Act: Section 7 Consultation Biological Opinion for the Marine Terminal Redevelopment Project at the Port of Anchorage. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Alaska Reg. (avail. online at https://alaskafisheries.noaa.gov/sites/default/files/poa_biop0709.pdf).

[8]Castellote, M., R. J. Small, J. Mondragon, J. Jenniges, and J. Skinner. 2016. Seasonal distribution and foraging behavior of Cook Inlet belugas based on acoustic monitoring. Alaska Dep. Fish Game, Final Wildl. Res. Rep., ADFG/DWS/WRR-2016-3, Juneau (avail. online at http://www.adfg.alaska.gov/static/home/library/pdfs/wildlife/research_pdfs/wrr_2016_3_seasonal_distribution_foraging_cook_inlet_belugas_acoustic_monitoring.pdf).

Table 1.—List of acoustic mooring locations and time periods selected for the anthropogenic noise study in Cook Inlet, Alaska, July 2008–May 2013. For each location, the month, year, and number of days of recordings that were analyzed for noise events is listed.

General area	Mooring location	Month, year (No. of days)	Total days
Upper Knik Arm	Eagle River	August 2010 (31) September 2010 (28)	59
Lower Knik Arm, west side	Six Mile	December 2011 (29) May 2012 (21)	50
Lower Knik Arm, east side	Cairn Point	August 2010 (31) April 2011 (3)	34
Upper Inlet	Fire Island	August 2009 (23) September 2009 (28)	51
Upper Inlet	Trading Bay	February 2012 (29) March 2012 (31) April 2012 (21)	81
Lower Inlet	Kenai River	April 2012 (21)	21
Lower Inlet	Tuxedni Bay	March 2012 (31)	31

gram allowed accurate measurement of received noise levels because the recording system is calibrated (Lammers et al., 2013). However, the measurement of high amplitude anthropogenic noises was compromised because these recording methods aimed to maximize detection of faint beluga signals (see Methodological Limitation #2 below). For this reason, we are only characterizing the noise events that exceeded the acoustic threshold for behavioral harassment (level B takes) for continuous sources (120 dB_{rms} for the lower inlet and 125 dB_{rms} for the upper inlet) and report when sources get near the 160 dB_{rms} impulsive threshold.

Noise events that could exceed the threshold for injury (level A takes) cannot be properly reported with these data because they exceeded the dynamic range of the recording system. Furthermore, the moorings were designed to survive the harsh conditions of upper Cook Inlet, rather than avoid self-noise generated by strong currents and debris hitting the mooring and acoustic instruments; such noise compromised the description of anthropogenic noise events occurring during high current periods.

Details of the sampled locations and recording periods selected for this study are listed in Table 1. For this study, upper inlet refers to all areas north of the East and West Forelands in Figure 1. A subset of these data were selected, on a monthly basis, to provide a representation of the diversity, spatial, and temporal occurrence of anthropogenic noise occurring in Cook Inlet beluga critical habitat (Table 1). The selection was based on the amount and diversity of anthropogenic noise found in the recordings when the data were analyzed for odontocete signals as part of the study's primary objective.

Specifically, recordings were selected from moorings deployed 1) near Anchorage (Cairn Point, Six Mile, and Fire Island), where anthropogenic activities are most concentrated and beluga presence is high; 2) at the mouth of Eagle River in Knik Arm, near military activities from the adjacent Joint Base Elmendorf Richardson (JBER) where belugas feed on Pacific salmon, *Oncorhynchus* spp., runs in summer and fall; and 3) in the mid- and lower inlet, areas where belugas may occur more frequently during winter and spring, overlapping with oil and gas production and commercial shipping (Fig. 1).

Overall, 14 months of recordings from seven mooring locations across all seasons from 2009 to 2012 were analyzed (Table 1). Selected data covered the months of February, March, April, May, July, August, September, and December. Areas that were monitored as part of the CIBA program but had little anthropogenic influence were not included in this study; similarly, areas where anthropogenic activities were abundant but belugas were absent were also not included. These selection criteria purposely focused noise analysis efforts on data from periods and locations with a strong overlap in beluga and anthropogenic noise occurrence.

Acoustic Recordings

Between 2008 and 2013 Ecological Acoustic Recorders (EARs, sensitivity of -193.5 dB, and flat response ±1.5 dB from 10 Hz to 28 kHz) were deployed year-round throughout Cook Inlet. EARs were deployed on custom designed low-profile moorings to resist the harsh conditions of the inlet (Lammers et al., 2013; Castellote et al., 2016). Acoustic data were sampled at a rate of 25 kHz, which resulted in recordings obtained from 0.01 to 12.5 kHz. A 10% duty cycle was used to prolong battery life which resulted in a recording file of 30 sec in duration every 5 min throughout the 24 h cycle.

Detection and Classification of Anthropogenic Noise Events

Raw data from binary EAR files were converted into ewav files for analysis; these files are similar to the standard sound wave (.wav) digital audio format. Analysis of ewav files was conducted using the MATLAB-based program Triton[9] (Scripps Inst. Oceanogr., La Jolla, Calif.) to view long-term spectrograms of ewav files, play back recorded sounds, and detect and classify anthropogenic noise events. Acoustic data were averaged over 5 sec to generate long-term spectrograms, but when measurements of specific selections occurred, the data were processed from uncompressed, non-averaged raw files. The following nine classes of anthropogenic noise events were identified (listed alphabetically):

1) Commercial ship,
2) Dredging,
3) Helicopter,

[9]Reference to trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

4) Jet aircraft—commercial or military non-fighter[10],
5) Jet aircraft—military fighter,
6) Outboard motor (small skiffs, rafts),
7) Pile driving (impact hammer method),
8) Propeller aircraft, and
9) Sub-bottom profiler.

As well as four repetitive unidentified noise sources:

10) Unclassified machinery (continuous mechanical sound; e.g., engine),
11) Unidentified "clank or bang" (impulsive mechanical sound; e.g., dumping hard material into a barge)[11],
12) Unknown up- or down-sweep (modulated tone of mechanical origin; e.g., friction originated by hydraulic systems), and
13) Unidentified (unclassifiable anthropogenic sound).

Classification of anthropogenic events was made manually by playing and inspecting the spectrogram of each signal. A classification scheme was developed using spectrogram images with sections of ewav files used as reference for comparison. Only unequivocally identified events were assigned to known noise source classes, and events whose source was uncertain were classed as "unidentified" or "unclassified" to minimize error. Only noises that were clearly from anthropogenic origin were included in the analysis.

If an event was detected in two or more consecutive files, it was presumed that this signal was sustained throughout the entire 5 min standby cycle. Multiple noise events that overlapped and events masked by self-noise from high current flow were only examined to account for their duration, but they were not used for other acoustic measurements since discerning acoustic energy from the overlapped events or from the event and the current flow noise was not possible. However, in many occasions, impulsive noises occurred only during continuous noise events. These were assumed to originate from the same source and thus were selected for the analysis (e.g., a towed barge could generate both the noise of the tug boat engine and clanking noises from the chains used to tow the barge).

The Port of Anchorage (POA) provided the "ship recall logs" for the periods of data analyzed. These logs present information on the temporal presence of commercial ships. Data from these logs were compared with recordings from the Cairn Point, Six Mile, and Fire Island moorings in an attempt to reclassify unclassified machinery events as commercial ship noise.

Arrival and departure times of commercial vessels were extracted from the POA logs and 30 min prior to arrival times in the log and 30 min after departure time in the log were considered to include tugboat operations associated with commercial vessels (Ribuffo[12]). Initially, a "tug boat" noise classification was used, but distinguishing between noise from tugs and commercial vessels was too challenging, often with complete overlap in occurrence. Thus, this noise class was not included in the analysis and both tug and commercial ship noise were grouped under ship noise class.

Noise Measurements

The system gain and frequency responses were factored in all noise measurements for each instrument, such that absolute dB values were obtained; i.e., re 1μPa (unless a different reference is specified).

Five acoustic metrics were calculated using custom written Matlab codes:

1) Root Mean Square (RMS) sound pressure level (SPL) (dB_{rms}): Calculated over the total duration of each event (defined in metric 3) and the full band of the recording (0.01–12.5 kHz). There were negligible differences in dB_{rms} when measured over the full band (0.01–12.5 kHz) or just over frequencies affected by each noise event, because most events influenced the full recorded range of 0.01–12.5 kHz.
2) Power spectral density in 1/3 octave band levels (in dB re μPa^2/Hz): Corresponds to mean values of 30 frequency bands for each noise class; results from this metric were processed to present a histogram with counts of 1/3 octaves with maximum amplitude (peak bands) per noise class. This histogram provides an overview of the dominant 1/3 octave bands for each noise class. Spectrum levels (in dB re $1\mu Pa^2$/Hz) for these dominant bands were calculated in Castellote et al.[13] and are stated in the results together with 1/3 octave band results.
3) Duration of event: measured as the difference between the end and start times, including recording standby periods when events spanned over multiple consecutive files. This metric is also provided as the mean duration and standard deviation for each noise class, including all the events detected in each location and month. For events occurring in sequences (i.e., pile driving, sub-bottom profiler, and clank or bang), the duration comprised the time elapsed from the onset of the first detected signal to the last one in the sequence. But see Methodological Limitation 2 related to this metric in the next section.
4) Sound exposure level (SEL, in dB re $1\mu Pa^2$-s): Defined as rms(SPL) + log(T) where T is the duration of the event, including standby periods when the detection spans

[10]In the figures, this noise class is labeled "Jet aircraft—military non-fighter" to reduce the length of the legends.

[11]Clank or bangs were discrete events but often occurred in series with random intervals.

[12]Ribuffo, S. Port Director, Anchorage. Personal commun., 2 Aug. 2013.

[13]Castellote, M., B. Thayre, M. Mahoney, J. Mondragon, C. Schmale, and R. J. Small. 2016. Anthropogenic noise in Cook Inlet beluga habitat: sources, acoustic characteristics, and frequency of occurrence. Final Wildl. Res. Rep. ADFG/DWC/WRR-2016-4. Alaska Dep. Fish Game, Juneau. (avail. online at http://www.adfg.alaska.gov/static/home/library/pdfs/wildlife/research_pdfs/wrr_2016_4_anthropogenic_noise_cook_inlet_beluga_habitat.pdf).

consecutive sound files or the interval between consecutive signals if they are generated in a sequence. Although we acknowledge that we have no control over changes in received levels (RL) during the standby periods. Note this metric is commonly described as cumulative SEL (L_E) by NMFS (2016).

5) Pressure in $dB_{zero\text{-}peak}$: Calculated by finding the maximum pressure in $dB_{0\text{-}peak}$ with a time resolution of 0.05s. This metric is suitable for impulsive signals and is a good replacement for sound pressure level (SPL) in dB_{rms} because signals of short duration are problematic for dB_{rms} calculation (Madsen, 2005).

Natural Ambient Noise Measurements

A substantial portion of our data was not considered to be a good representation of the natural ambient noise conditions in Cook Inlet (i.e., background noise without self-noise or anthropogenic contribution) due to the amount of anthropogenic noise events in all the locations sampled. Therefore, to minimize the effects of anthropogenic noise, measurements were done only with recording periods excluding any anthropogenic noise event. Using custom written Matlab code, these recording periods were binned in 5 min intervals to calculate SPL over the full band of the recording (0.01–12.5 kHz), and power spectral density percentiles for each mooring location and month. Percent of time below 120 dB_{rms}, within 120–125 dB_{rms}, and above 125 dB_{rms} was also calculated. It should be noted that for most sampled locations in the upper inlet, high water current levels generated flow noise at the hydrophone, and vegetative debris colliding with the moorings caused impulsive noise. These artificially elevated noise periods occurred periodically, were not removed for the analysis, and are reflected in the higher end dB values reported here.

Comparisons to Beluga Hearing

Noise class and natural ambient noise spectral density results were compared against current knowledge on beluga whale hearing thresholds (Awbrey et al., 1988; Castellote et al., 2014) to highlight the potential for hearing and communication masking. Two factors play an important role in this comparison. The first factor is that only a few studies describe beluga critical ratios and auditory filters, with a limited number of animals sampled and varied methods, providing high variability in results (Johnson et al., 1989; Klishin et al., 2000; Finneran et al., 2002; Erbe et al., 2008). The second factor is the unknown capacity of belugas to cope with masking noise, and the potential for masking release mechanisms, is a topic barely studied in beluga whales (Erbe et al., 2016). Thus, as a first step in this comparative approach, we have used a frequency summation of 1/3 octave bands, a common and conservative bandwidth over which to compare spectral density results to hearing thresholds. We have not attempted to factor critical ratios or masking release mechanisms into the comparison between hearing thresholds and spectral density of detected noise, thus our results should be considered conservative. More details on beluga masking release, auditory filters, and critical ratios would be required to improve this comparative approach.

Methodological Limitations

Because the study was designed primarily to collect data relevant to the long-term detection of beluga whale signals (Lammers et al., 2013; Castellote et al., 2016) and not anthropogenic noise, three important limitations must be acknowledged:

1) Recorder power consumption was a limiting factor for long-term recordings. The sampling rate and the duty cycle were adjusted to reduce power consumption in each recorder. Since the primary objective of this study was to detect beluga vocalizations, a sampling rate was selected high enough to collect the frequencies where most of the acoustic energy of beluga social calls is centered, (0.01–12.5 kHz; Lammers et al., 2013). Any anthropogenic noise generating acoustic energy only above 12.5 kHz would not be detected in our recordings. Although this is a limitation, most of the anthropogenic noises had acoustic energy below 12.5 kHz. Only depth/fish sounders, scientific echo sounders, and military sonar are able to generate acoustic energy exclusively above 12.5 kHz. Of these, only depth/fish sounders are commonly used in Cook Inlet, although these noise sources are always associated with shipping noise, which is detected within the 0.01–12.5 kHz.
2) The duty cycle (10%) used to obtain months-long deployment durations resulted in sound files of 30 sec in duration. Noise events longer than 30 sec or truncated at the beginning or end of the 30 sec files, resulted in all pressure-related measurements (i.e., SPL, SEL, peak pressure) being inherently conservative; duration measurements, however, were only partially truncated because the standby interval was accounted for when signals lasted more than one consecutive file. The total number of events or the total time for each noise class and its reported percentage is underrepresented because any event that fell into the standby period could not be detected. Therefore, absolute presence of anthropogenic noise cannot be directly measured with these data.
3) For all CIBA deployments, the recording gain was set on the EARs to enhance the detection of faint, far away beluga vocalizations. This gain setting shifted the dynamic range of the recorder to lower received levels and compromised the recording quality of high amplitude signals, as they become saturated by too much gain and are no longer useful to reliably provide any sound pressure-based characteristic. Signals with sound amplitude higher than 153 dB (peak to peak) were at the limit of the EAR system to accu-

rately record the signal. For a perfect sinusoid wave the SPL in dB_{rms} will be 9 dB below the peak value, putting the SPL dB_{rms} upper limit at 144 dB. When 153 dB peak or 144 dB_{rms} is exceeded, the recorded waveform becomes clipped (i.e., the upper and lower limits of the waveform are cut). While clipped signals are still recorded and can be identified, measurements of their magnitude or contribution at different frequencies becomes biased. This limitation impedes an accurate assessment of signals with the highest dB levels. For the survey of the density and distribution of noise events, clipped events were included with non-clipped events in the results. Because of this limitation, overall sound pressure and sound exposure levels should be considered lower than what was present in the study area. See the CIBA final report on anthropogenic noise (Castellote et al.[13]) for an occurrence analysis of clipped events.

Additionally, one more methodological limitation inherent to mooring sound recorders in the upper section of Cook Inlet is the high current periods associated to the extreme tidal cycles that typically occur in this region. Large tides, exceeding 10 m, produce strong currents and tidal bores with speeds of up to 5 m/sec (Ezer et al., 2008). The flow noise generated by high water flow around a static hydrophone capsule is dependent on the intensity of turbulence and the transducer geometry and is observed to frequencies greater than 500 Hz. (Bassett et al., 2014). Some recorders have been fitted with a flow shield made of open cell foam or mesh around the hydrophone capsule to reduce flow noise (e.g., Greene et al., 2004); however, in Cook Inlet, because of the high density of suspended glacial silt throughout the water column (>1700 mg/l near Anchorage; Wright et al., 1973), flow shields would quickly get clogged with silt increasing sound attenuation and altering the system's frequency response. Only deployment locations in the upper inlet were affected by flow noise (Eagle River, Six Mile, Cairn Point, and Fire Island) during current peak periods.

Results and Discussion

Spatial and Temporal Occurrence of Anthropogenic Noise

A total of 6,263 anthropogenic acoustic events were present in the 8,756 h of data selected for our analysis. These events had a summed duration of 1,025 h which represented 11.7% of the sound recordings analyzed. In total, we identified 13 anthropogenic noise classes. The presence of anthropogenic noise in only 11.7% of the selected data could be inferred as a minor disturbance; however, anthropogenic noise was neither homogenously distributed across the inlet nor across seasons, and areas and periods of high noise concentration were common.

In general, during winter months the lower inlet was much quieter than the upper inlet. When measuring the temporal persistence of each noise class by location and month, commercial shipping noise dominated the soundscapes in both the upper and lower inlet, except in Eagle River, as this location is not navigable for commercial vessels and was the least disturbed of all sampled locations.

Commercial ship noise events were slightly longer in duration in the lower inlet compared to the upper inlet, which could be related to differences in speed. Ships moving slower in the upper inlet will cause lower source levels and shorter detection ranges. But longer durations in ship noise could also be related to improved sound propagation by deeper and less restricted waters in the lower inlet.

Figure 2 shows a clear comparison of overall mean SPL for detected anthropogenic noise in each sampled location and month. The highest amplitude and longest anthropogenic activities occurred at Cairn Point, the mooring location closest to the POA, particularly in summer. When considering the amount of recording time and the total duration of anthropogenic noise event in each location, the highest percentage of time with anthropogenic noise (50.3%) and the highest number of noise sources also occurred at Cairn Point (Table 2). The seasonal increase in number of events at Cairn Point is due to increased port activity when ice is absent (generally May to October). Other summer-related activities in this area also increased (e.g., operative public launch ramp, port dredging operations, etc.). These changes are clearly evident by the substantial difference in the number of detected events per day for each class at Cairn Point in April (19.3) vs. August (153.5) in Table 2.

The lower section of Knik Arm is a particularly important beluga corridor in summer. Belugas must pass by the Cairn Point area when moving into and out of Knik Arm, which is considered an important foraging area within their critical habitat (NMFS, 2008) and potentially a nursery area (Huntington, 2000; Hobbs et al., 2015). Saxon Kendall et al. (2013) suggested that belugas might be displaced towards the west side of lower Knik Arm when transiting the Cairn Point area due to the noise generated along the eastern shore near the POA. The duration and diversity of anthropogenic noise classes are relatively similar between Cairn Point and Six Mile (Table 2, Fig. 3), yet the amount of detected events per day at Cairn Point was much higher than at Six Mile (Table 2).

Our results indicate that although physical displacement of belugas from the waters around the POA could reduce their exposure to anthropogenic noise as the whales transit through the lower Knik Arm, the exposure is still considerable at the western side of lower Knik Arm. Specifically, Port MacKenzie is located on the west side of the arm, and even if this is a smaller port than POA, a bulk head barge dock and a deep-draft dock are commonly used there.

Activities at Port MacKenzie are likely important contributors to anthropogenic noise on the western side

Table 2.—Anthropogenic noise classes and number of events, grouped by location and month, detected in the seven locations sampled in Cook Inlet, Alaska, during the period August 2009–May 2012. Note that different noise classes were detected in each location, and some months were not entirely sampled.

Location Month	Noise class	No. of events
Eagle River		
August 2010 (31 days)	Aircraft-non-fighter	1
	Jet aircraft-military fighter	30
	Outboard motor jet	21
	Propeller aircraft	2
	Unidentified	1
	Monthly total	55
	No. of events/day	1.8
September 2010 (28 days)	Jet aircraft-military fighter	38
	Outboard motor	7
	Unidentified	4
	Monthly total	49
	No. of events/day	1.8
Six Mile		
May 2012 (21 days)	Jet aircraft-non-fighter	4
	Commercial ship	42
	Dredging	27
	Jet aircraft-military fighter	4
	Pile driving	22[1]
	Unclassed machinery	5
	Unidentified clank bang	11
	Monthly total	115
	No. of events/day	5.5
December 2011 (29 days)	Jet aircraft-non-fighter	22
	Commercial ship	22
	Helicopter	7
	Jet aircraft-military fighter	1
	Unclassed machinery	73
	Unidentified	2
	Unidentified clank bang	4
	Monthly total	131
	No. of events/day	4.5
Cairn Point		
April 2011 (3 days)	Commercial ship	5
	Dredging	42
	Outboard motor	4
	Propeller aircraft	3
	Unclassed machinery	1
	Unidentified	1
	Unidentified clank bang	2
	Monthly total	58
	No. of events/day	19.3
August 2010 (31 days)	Jet aircraft-non-fighter	7
	Commercial ship	1,832
	Dredging	36
	Jet aircraft-military fighter	13
	Unclassed machinery	412
	Unidentified	109
	Unidentified clank bang	1,884
	Unknown up or down sweep	464
	Monthly total	4,757
	No. of events/day	153.5
Fire Island		
August 2009 (23 days)	Jet aircraft-non-fighter	11
	Commercial ship	155
	Jet aircraft-military fighter	3
	Outboard motor	10
	Pile driver	24[1]
	Sub-bottom profiler	1[1]
	Unclassed machinery	26
	Unidentified	32
	Unidentified clank bang	14
	Monthly total	276
	No. of events/day	12
September 2009 (28 days)	Jet aircraft-non-fighter	35
	Commercial ship	123
	Jet Aircraft-military fighter	1
	Propeller aircraft	2
	Unclassed machinery	3
	Unidentified	17
	Monthly total	181
	No. of events/day	6.5
Trading Bay		
February 2012 (29 days)	Commercial ship	94
	Unclassed machinery	23
	Monthly total	117
	No. of events/day	4
March 2012 (31 days)	Commercial ship	88
	Unclassed machinery	115
	Unidentified clank bang	1
	Monthly total	204
	No. of events/day	6.6
April 2012 (21 days)	Commercial ship	62
	Unclassed machinery	144
	Unidentified	2
	Monthly total	208
	No. of events/day	10
Kenai		
April 2012 (21 days)	Commercial ship	70
	Jet aircraft-non-fighter	2
	Outboard motor	6
	Pile driving	1[1]
	Propeller aircraft	1
	Sub-bottom profiler	1[1]
	Unclassed machinery	3
	Unidentified	1
	Monthly total	85
	No. of events/day	4
Tuxedni		
March 2012 (31 days)	Commercial ship	22
	Propeller aircraft	1
	Unclassed machinery	1
	Unidentified	3
	Unidentified clank bang	1
	Monthly total	28
	No. of events/day	1

[1]These values reflect the number of sequences detected but not the number of events within each sequence.

of lower Knik Arm. Importantly, anthropogenic noise in this area is concentrated in the summer months (Table 2), when belugas use this area more intensely, accessing the upper areas of Knik Arm to feed on anadromous fish runs such as eulachon, *Thaleichthys pacificus*, and salmon (Goetz et al., 2012).

Persistent shipping noise was recorded at Trading Bay but at lower received levels than Cairn Point or Fire Island (Fig. 4A). The main shipping route to or from Anchorage is further away from the Trading Bay mooring than the Fire Island and Cairn Point moorings, so the shipping noise in Trading Bay may be from activities associated with the numerous offshore oil and gas platforms (Fig. 1). Unclassified machinery noise was very persistent in Trading Bay and was likely related to the high concentration of oil and gas production operations in this area (subsea production machinery, pipelines connecting offshore platforms to land facilities, etc.). The acoustic footprint of this industry has barely been described in Cook Inlet, and thus many of the recursive machinery noises detected here remain unclassified.

Eagle River and Tuxedni Bay were the two locations with the lowest overall occurrence of anthropogenic noise and lowest overall mean SPL for anthropogenic events (98.8 and 98.9 dB_{rms}, respectively, Fig. 2). Both areas are relatively isolated from anthropogenic activities. Eagle River is mainly exposed to jet aircraft noise (Table 2) due to its proximity to the JBER. Noise from the Army's live fire training and detonations of high explosives on land were not detected. Outboard motor noise was also common in Eagle River, likely from small research vessels (e.g., JBER beluga studies, LGL photo-id studies) and occasional small fishing vessels transiting through the area. The upper Knik Arm sustains

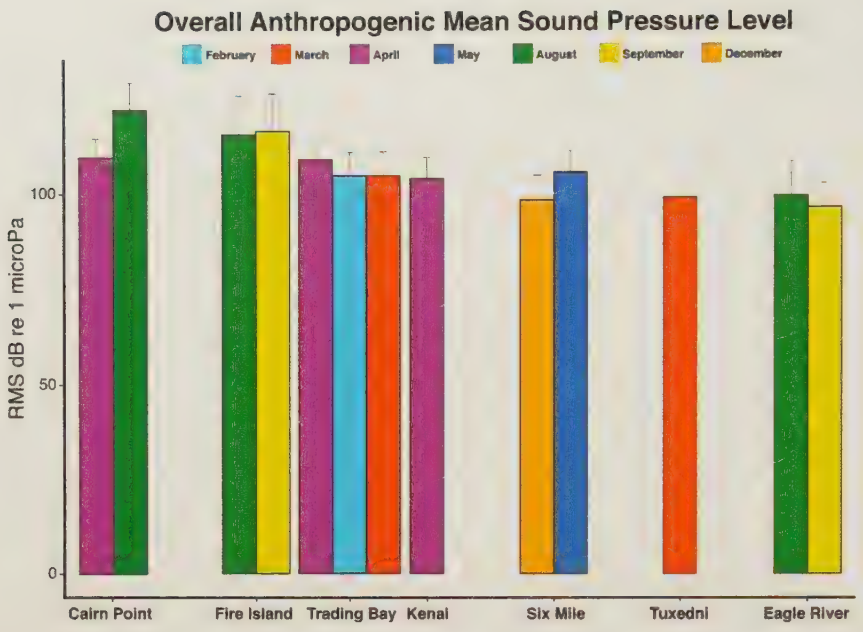


Figure 2.—Overall mean anthropogenic sound pressure level (SPL) calculated as dB_{rms} re 1 µPa and standard deviation from all the anthropogenic noise events of each location and month, independently of the noise class. Locations are ordered from noisiest to quietest. Only months where data was sampled are included in the figure.

an important sport fishery but most of these small vessels access the Matanuska River and Knik River from boat launches in the lower portion of the rivers themselves (ADFG, 2015).

Anthropogenic Noise Contributors in Cook Inlet

Commercial Shipping

Commercial ships were the most prominent source of anthropogenic noise across Cook Inlet both in percent of overall anthropogenic noise time (63% on average) and mean duration of the events (Fig. 3) and, for Fire Island, received SPL (mean of 119.9 dB_{rms}, Fig. 4A). For most locations, commercial shipping contribution to the background noise was well above the levels reported for heavy traffic by Richardson et al. (1995). Mean received SPLs at Cairn Point were very close to the levels at Fire Island (a difference of just 1.4 dB), probably due to the proximity of the shipping route to the mooring locations (Fig. 1), but might also be related to the range over which tug boats assist vessels when approaching or departing the port facilities.

The 1/3 octave band analysis for ship noise showed that most events peaked in the band centered at 630 Hz or near this band (Fig. 5A). The spectrum levels for these dominant 1/3 octaves exceeded 115 dB re 1 $\mu Pa^2/Hz$ (Castellote et al.[13]). Lower frequencies, which are typically affected by ship noise, might have been affected by the shallow water propagation conditions of Cairn Point. Hearing threshold for belugas at these peak frequency bands is approximately 108 dB (Awbrey et al., 1988). All other 1/3 octave bands above the one centered at 630 Hz showed received levels that were also exceeding hearing thresholds (Awbrey et al., 1988; Castellote et al., 2014); therefore, commercial ship noise could potentially mask beluga hearing and interfere with their communication in all sampled locations.

Ship noise levels in Saguenay Fjord, St. Lawrence Estuary, Can., were reported in the range 102.1–114.1 dB_{rms} (Gervaise et al., 2012). These authors estimated that when ship noise was highest, beluga communication and echolocation range was reduced by up to 85% of its expected value compared to natural noise conditions. Over 79% of our reported SPL values for commercial ship noise were above 114.1 dB_{rms} (Fig. 4A), therefore the potential communication and echolocation range reduction for Cook Inlet belugas may be even more extreme than in the Saguenay Fjord. Due to the clipping of commercial ship noise events at high levels, our data preclude an accurate description of the highest received levels. However, the results presented here are sufficient to highlight the potential for the acute masking of beluga communication over a wide temporal and spatial scale within their critical habitat.

Shipping traffic in Cook Inlet is reduced in winter by 15–20% and shipping speeds are lower when thick ice is present, but also the shipping route might be altered towards the east in the mid-inlet to avoid denser ice areas (Garay[14]). These changes could explain a reduction in noise levels for winter months, particularly for the western side of the mid-inlet (e.g., Trading Bay).

Six Mile is near Port MacKenzie but ship noise occurrence is lower and their SPLs (mean of 104.5 dB_{rms}) are not as high as in Cairn Point (mean of 118.5 dB_{rms}). However, highest received levels for ship noise events still exceeded 120 dB_{rms} at Six Mile. Even if belugas could potentially be displaced towards the western side of the arm (Saxon Kendall et al., 2013), they would still be exposed to substantial ship noise levels. Figure 6 shows how ship noise SEL at both Cairn Point and Six Mile falls within approximately 125 to 150 dB with medians at 139 dB and 134 dB, respectively. This suggests that when beluga are exposed to ship noise at the lower part of Knik Arm, the exposure might not be very different on either side of the arm.

[14]Garay, P. Southwest Alaska Pilots Association, Homer, Alaska. Personal commun., 6 Oct. 2015.

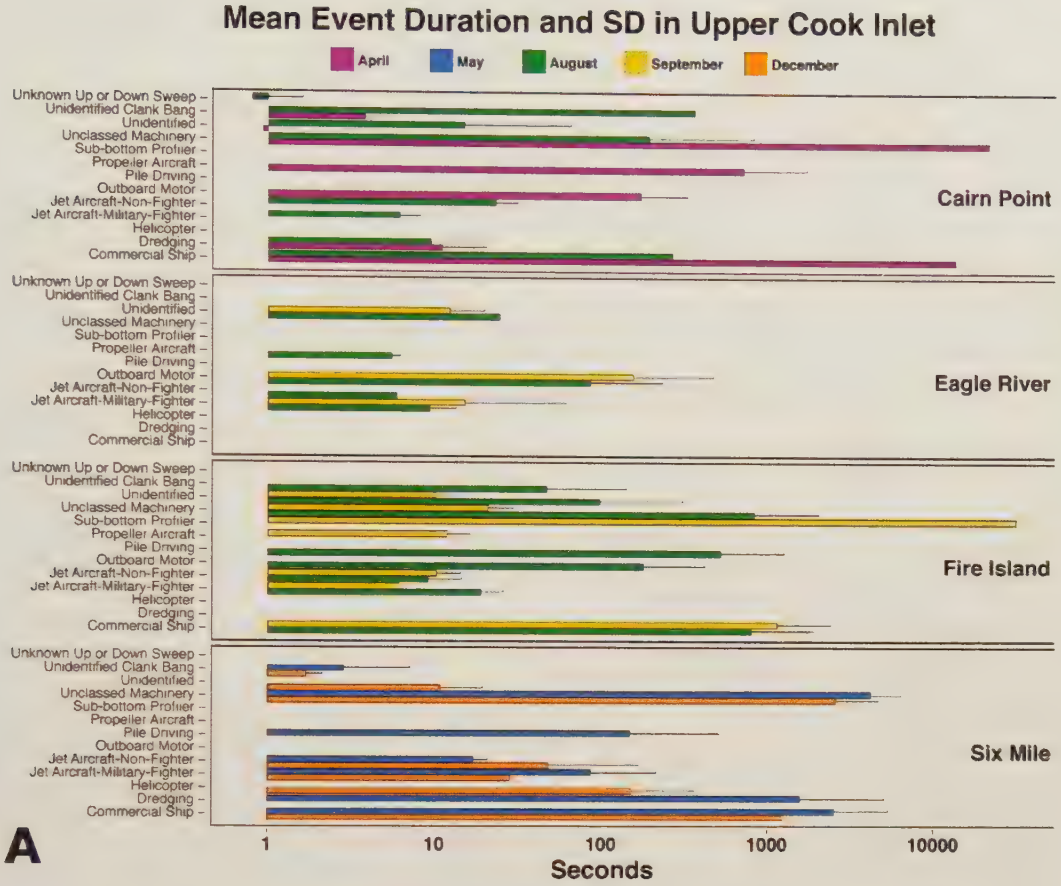


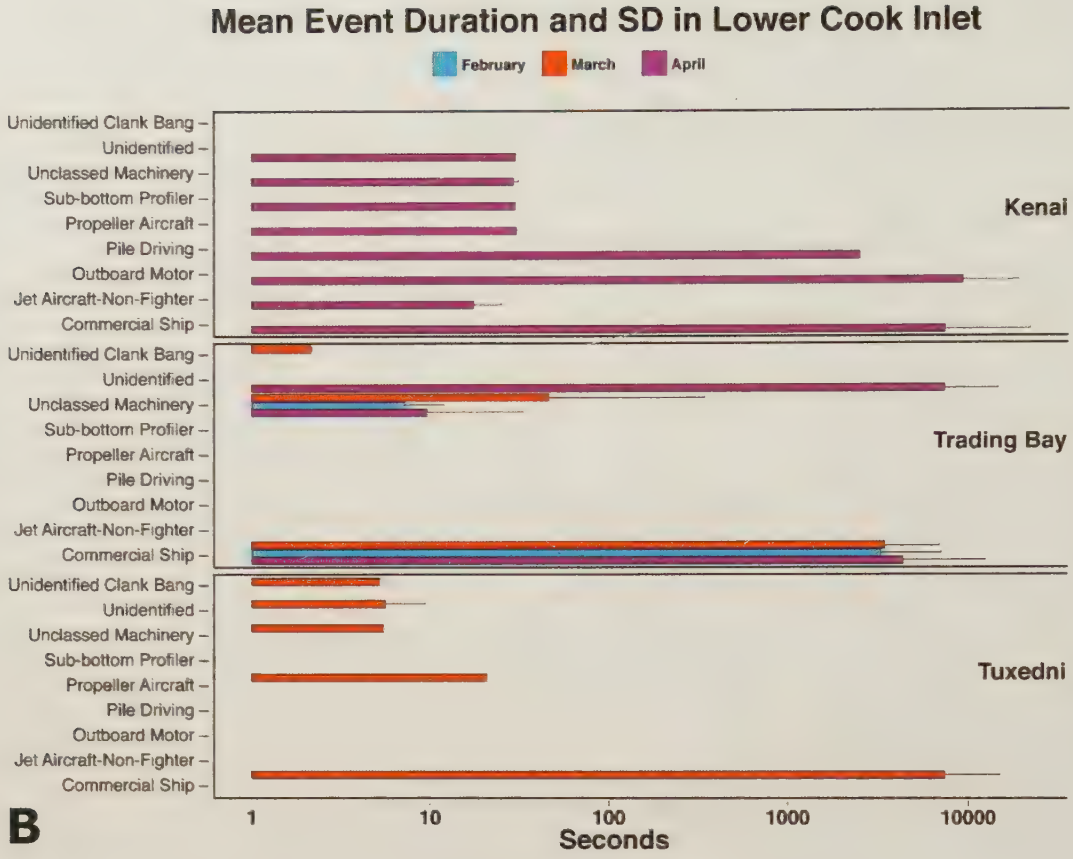
Figure 3.—Mean duration and standard deviation of noise classes detected at each site by month. Upper panel (A) includes the 4 locations sampled in the Upper Inlet (Cairn Point, Eagle River, Fire Island and Six Mile), and the lower panel (B) includes the 3 locations sampled in the Lower Inlet (Kenai, Trading Bay and Tuxedni). Note that a maximum of 3 mo per location were selected (see Table 1), therefore, not all months were sampled in all locations.

Jet Aircraft Noise

Because of the presence of the JBER in the vicinity of Knik Arm as well as the Anchorage International Airport, aircraft noise from commercial (e.g., 727, 747), fighter (e.g., F-15, F-22), and non-fighter military jets (e.g., C-17, E-3a) is a prevalent source of underwater noise in upper Cook Inlet, but is absent in the lower inlet. Distinguishing between commercial and military non-fighter jet aircraft was difficult as their underwater acoustic signatures were very similar. Therefore, these events were grouped in a single noise class termed jet aircraft. However, it is likely that events of this noise class in mooring locations closer to JBER are military non-fighter jet aircraft and events in mooring locations closer to the Anchorage International Airport are commercial jet aircraft.

Jet aircraft (non-fighter) was of highest amplitude in Cairn Point (mean of 125.7 dB_{rms}, maximum of 135.9 dB_{rms}, Fig. 4B), likely due to the proximity to the JBER. Fire Island is the second highest amplitude location for this noise class (mean of 106.2 dB_{rms}, maximum of 126.44 dB_{rms}, Fig. 4B) because the path for landing and take-off from the Anchorage International Airport east–west runways cross over this mooring location. The mooring location at Fire Island is further away from the airport than the mooring location at Cairn Point is from the JBER, thus aircrafts tend to be higher in altitude than at Cairn Point, and the received SPLs tend to be lower.

Jet fighter noise occurrence was highest at Eagle River, but received levels (mean of 95.3 dB_{rms}, maximum of 104.8 dB_{rms}, Fig. 4C) were consistently lower than at Cairn Point (mean of 124.8 dB_{rms}, maximum of 135.4 dB_{rms}, Fig. 4C). The mooring location at Cairn Point was within the path for landing and take-off from the east–west runway at the JBER, and the mooring at Eagle River was in the path of the north–south runway but at a much larger distance. These results suggest that, for the months sampled, the north–south runway was more



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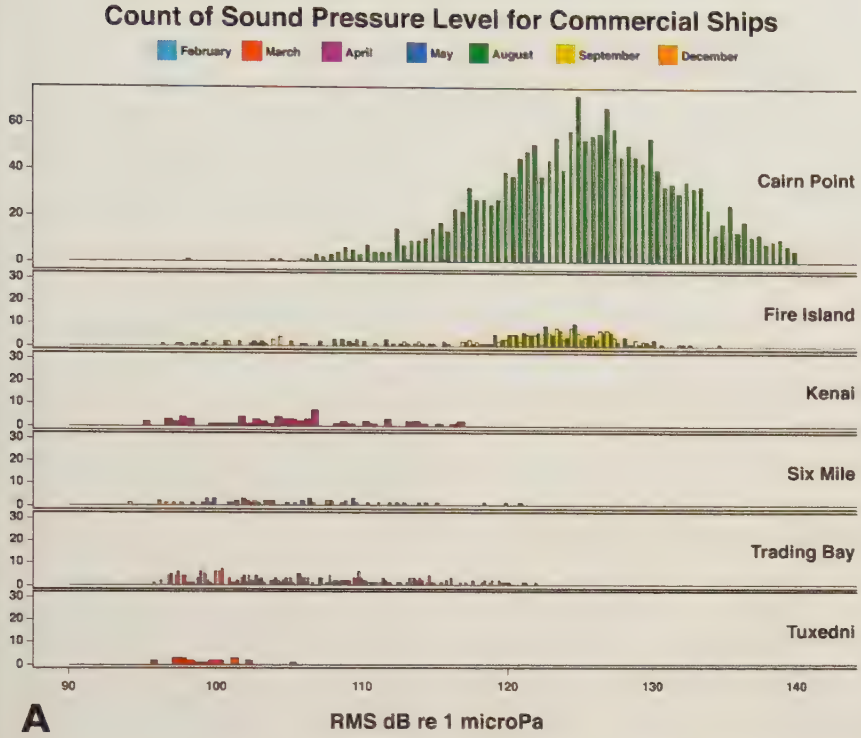
commonly used by jet fighters, and their overpass altitude was higher at Eagle River than Cairn Point.

Third octave band peak energy commonly occurred at the 315 Hz band for jet fighter noise and at more variable bands for other jet aircraft (Fig. 5B and 5C). Beluga hearing threshold was exceeded by all bands above 500 Hz for both types of jet noise (Awbrey et al., 1988; Castellote et al., 2014). Thus, beluga can hear both jet aircraft and jet fighter noise when these happen, and this has the potential to generate masking of their hearing and communication signals. But, both jet aircraft and jet fighter noise events were always of very short duration (overall average of 14.2 sec for jet aircraft and 10.4 sec for jet fighter noise).

Jet fighter noise occurrence ranged from 0 to 4 events per day at Cairn Point (April and August), from 0 to 6 events per day at Fire Island (August and September), and from 0 to 9 events at Eagle River (August and September), which is representative for a 10% duty cycle recording scheme. Therefore, its equivalence would be 0 to 40 events per day at Cairn Point, 0 to 60 at Fire Island and 0 to 90 at Eagle River for the sampled months, although this assumes homogenous distribution of jet overpasses throughout the day, which is not realistic. Because the behavioral response of Cook Inlet belugas to jet aircraft and jet fighter noise in unknown, it is not clear if this noise disturbance should be a concern. Even if peak frequency bands are within the beluga hearing range, and received levels exceed the behavioral harassment threshold of 125 dB_{rms} for some events, this sporadic and brief disturbance is unlikely to negatively impact belugas, unless these reach higher levels than the ones reported in this study.

Dredging

Dredging occurred in the turning basin of the POA and at the docks during the sampled months, which explains why this noise source was only detected at Cairn Point and Six Mile (Table 2). This noise class was difficult to discern from other shipping related noise sources as it involves a tug boat and barge and could be an important contributor in other noise classes such as "unclassed machinery" and "unidentified." Received SPL values reported higher sound amplitudes, particularly in August, at Cairn Point (mean of 121.2 dB_{rms}) than at Six Mile (mean of 107.8 $dB_{rms;}$ Fig. 4D). However, SEL values indicate the opposite (mean SEL of 127.7 dB vs. 130.6 dB). These discrepancies between metrics reflect



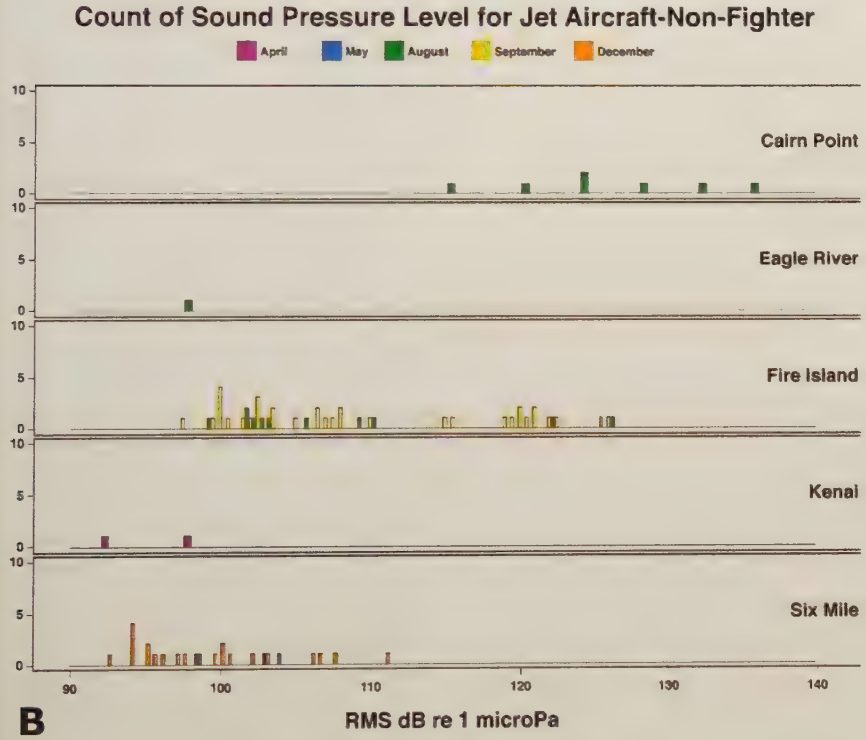


Figure 4.—SPL in dB_{rms} by noise class, month and location from anthropogenic noise events detected in the sampled locations in Cook Inlet, Alaska. Noise classes included are A) commercial ship, B) jet fighter, C) jet aircraft (commercial or military non-fighter), D) dredging, E) outboard motor, F) pile driving, G) unclassed machinery, H) unidentified, I) unidentified clank or bang, and J) unknown down or up sweep. Note that not all noise classes were detected in each location and month sampled. For all other noise classes see Castellote et al. (2016c).

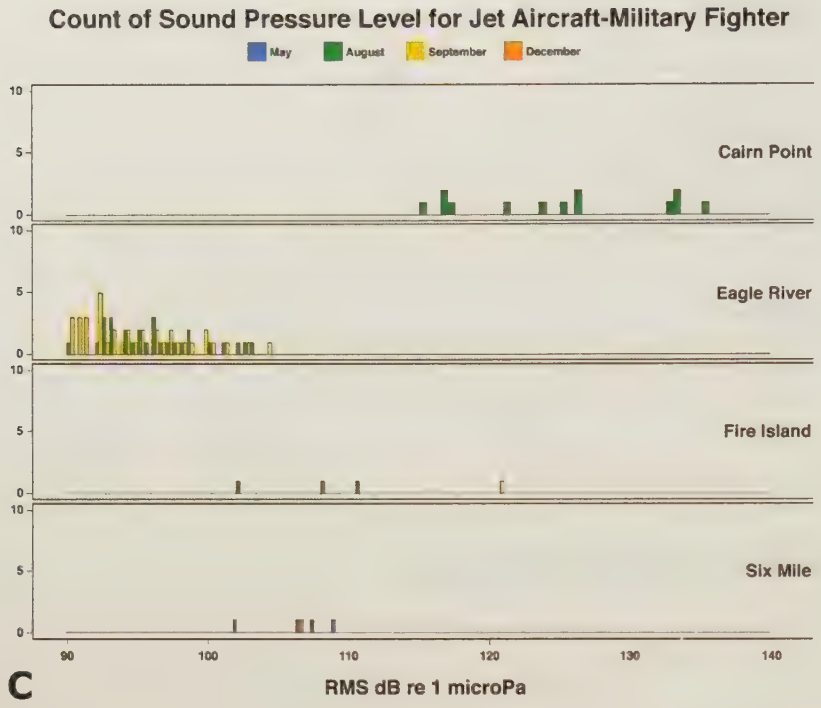
longer duration of events at Six Mile than Cairn Point (Fig. 3A), and could be related to the different locations dredged among the sampled months, and different dredging methods used (e.g., both a clam shell and a hopper system were used in the POA during the sampled period) (Anderson[15]).

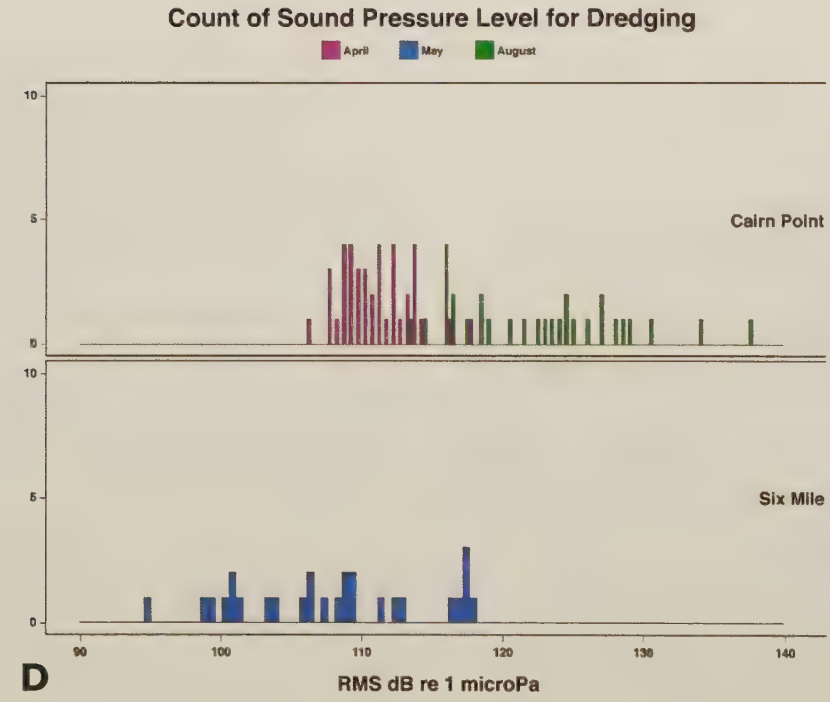
For most events, the peak amplitude fell into the 1/3 octave band centered at 793 Hz (Fig. 5D). Averaged received spectrum levels for this band exceeded 110 dB re 1 $\mu Pa^2/Hz$, which is above the beluga hearing threshold (Awbrey et al., 1988), and all the 1/3 octave band levels above this frequency were also above the hearing thresholds (Awbrey et al., 1988; Castellote et al., 2014), therefore beluga hearing and communication may be masked by dredge noise at the locations and months sampled here. The detection of multiple events of dredge noise at Six Mile indicates that belugas are exposed to this noise source even if they avoid the eastern side of the lower Knik Arm, where most of the dredging operations occur. Six Mile SPLs for this non-impulsive source did not exceed 125 dB_{rms} but maximum SPLs at Carin Point reached 137.1 dB_{rms}. It is likely that closer to the dredging area, radiated noise might well exceed 125 dB_{rms} across the arm and would therefore expose any beluga that enters or exits Knik Arm to levels of noise exceeding the current behavioral harassment threshold.

Outboard motor

Outboard motor noise was detected at Eagle River, Cairn Point, Fire Island, and Kenai. Received SPLs varied (mean 107.6 dB_{rms}, maximum of 131.4 dB_{rms}; Fig. 4E) and probably reflect the different distances at which these noise sources were detected rather than differences in the noise source itself. In total, there were 48 events detected in three different months, suggesting that outboard motors are often used in Cook Inlet, at least from April to September. However, their acoustic

[15]Anderson, J. Chief of Operations at the U.S. Army Corps of Engineers' Alaska District. Personal commun., 25 Nov. 2014.





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disturbance is short-lived, on average 2.5 min (except for Kenai, see below).

Outboard motor noise typically presents strong harmonic contents. This is reflected by the higher number of energy peak values in the 1/3 octave bands centered at 397 Hz, 1000 Hz and 8000 Hz (Fig. 5E). Peak 1/3 octave band levels only exceed beluga hearing at 8000 Hz and higher (Castellote et al., 2014). Because beluga hearing is more sensitive at higher frequencies, this noise source might cause stronger interference to beluga hearing and communication, however, because of its short duration, and low density of occurrence, this acoustic disturbance might not be a concern for Cook Inlet belugas. An exception to this conclusion is Kenai. A total of 21 days in April 2012 were sampled for this study detecting outboard motors with average durations of 2.5 h, and maximum of 6.9 h. When these detections were reviewed, the detection period included what look like multiple outboard motors used concurrently for long periods of time each day. These results suggest intense use of outboard motors in the area throughout the day, at least in April. Small boats and rafts are common at the mouth of Kenai River during the fishing season. The City of Kenai operates four public launch ramps at the mouth of the river, the only ones available in the area, and it is home to many commercial fish processing and cannery operations. Kenai is also a world-class sport fishing area. However, April is too early for most fishing operations, except the eulachon dip net fishery, opening on 1 April, and rafts and boats being tested in preparation for the fishing season (Marston[16]). We did not sample later months in the season at Kenai, but these results suggest that fishing activities at Kenai River, starting in April, might introduce a strong seasonal acoustic disturbance at this important beluga feeding habitat. Furthermore, the results discussed here should be placed in a behavioral con-

[16]Marston, B. Northern Kenai Peninsula Area Fisheries Biologist, Alaska Dep. Fish Game. Personal comm., 15 March 2016.

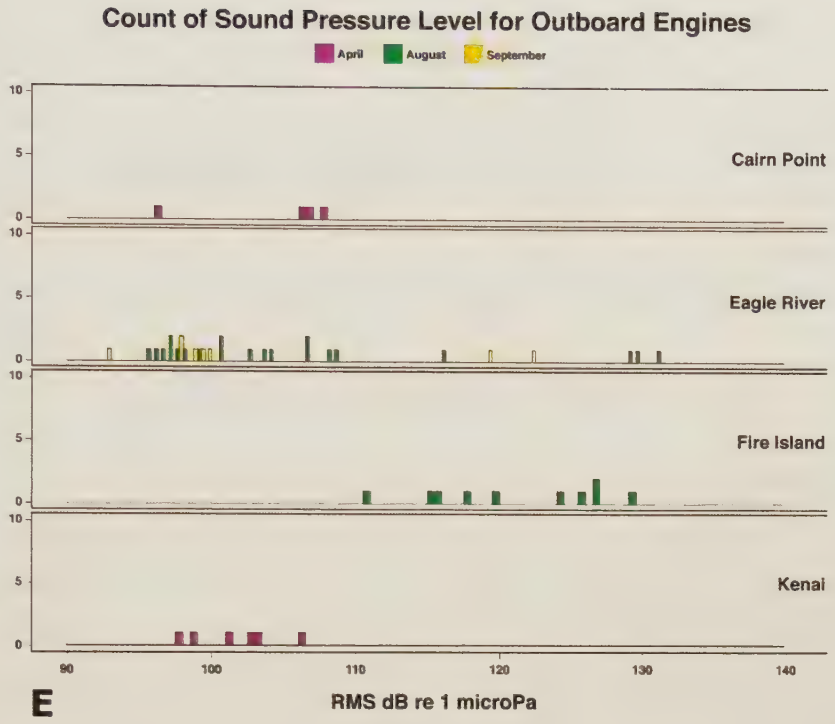
text. The exposure to outboard motor noise, in terms of spectral density or duration, might moderately disturb the acoustic space of belugas, but if belugas are sensitized to this noise source, its presence in the environment could trigger strong behavioral reactions such as spatial displacement. Sensitization occurs when the noise stimulus could generate physiological damage and is recurrently used (Bejder et al., 2009). Cook Inlet belugas have been hunted from small boats operated by outboard motors since the 1930's, and are known to be sensitized to outboard noise (Huntingon, 2000).

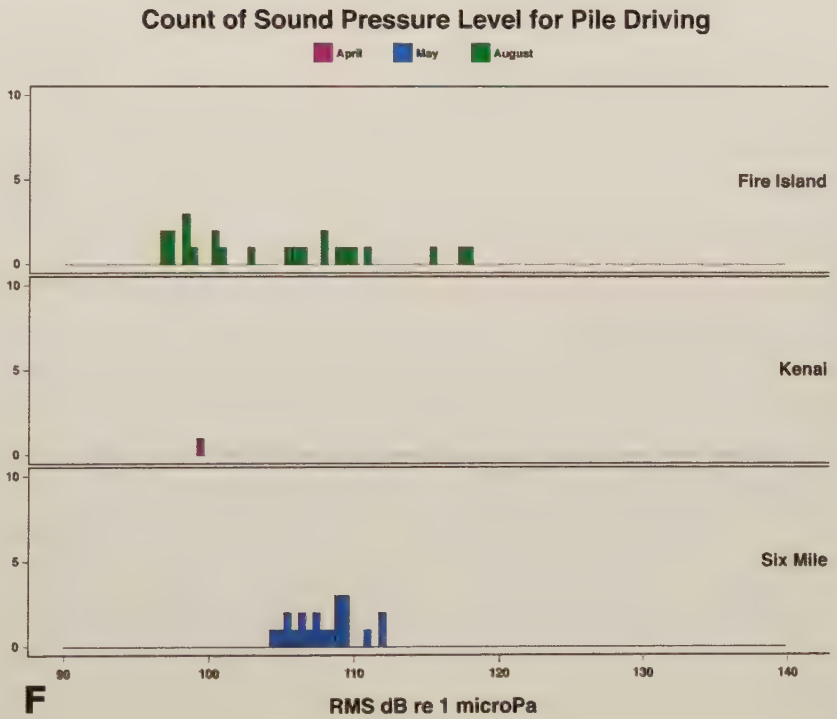
Pile Driving

Impact pile driving noise was detected at three different sites in three different months. Detections at Six Mile in May 2012 correspond to the Cook Inlet Tug and Barge Company's trestle and barge float improvements near the POA. Detections at Fire Island in August 2009 correspond to the POA Marine Terminal Redevelopment Project at the north extension of the port. Neither NMFS nor the U.S. Army Corps of Engineers are aware of any piling activity that corresponds to the single detection of approximately 30 minutes (Fig. 2B) at Kenai in April 2012 (Mahoney[17]).

Pile driving activity is a well-studied acoustic disturbance of primary concern for the impact to marine mammals (Dahl et al., 2015). NMFS currently evaluates any application for pile driving in Cook Inlet, with particular concern to potential impact on belugas, and multiple mitigation procedures are requested as part of the permitting process. It is surprising that a pile driving operation was identified in Kenai in April 2012 without any related permit.

The Cook Inlet Tug and Barge Company's operation involved three 12-inch steel cylindrical piles and nine 24-inch steel piles. Impact pile driving was detected at a distance of 6 km (Six Mile) with mean received levels of





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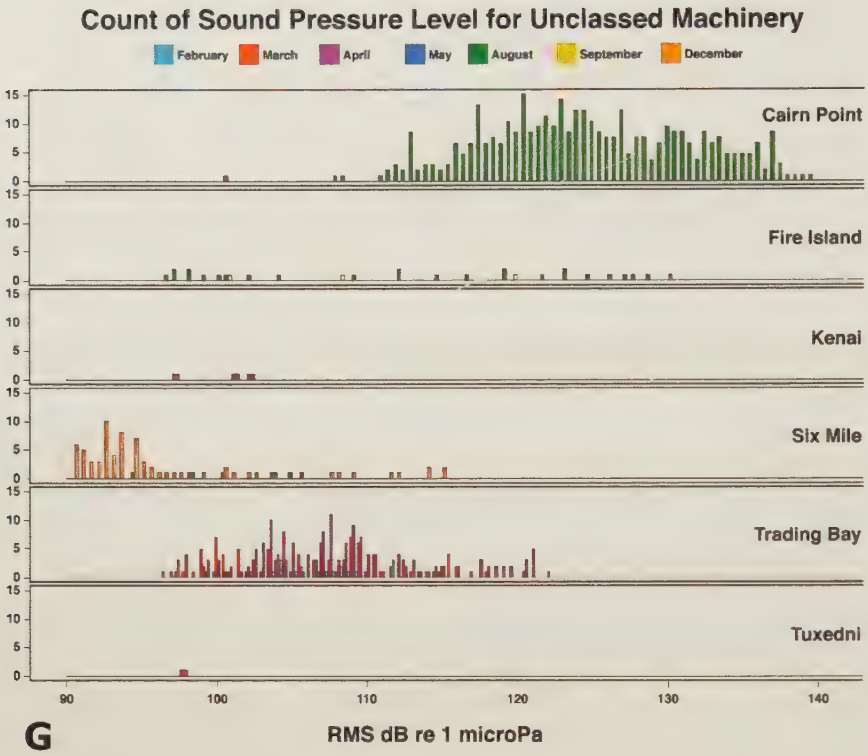
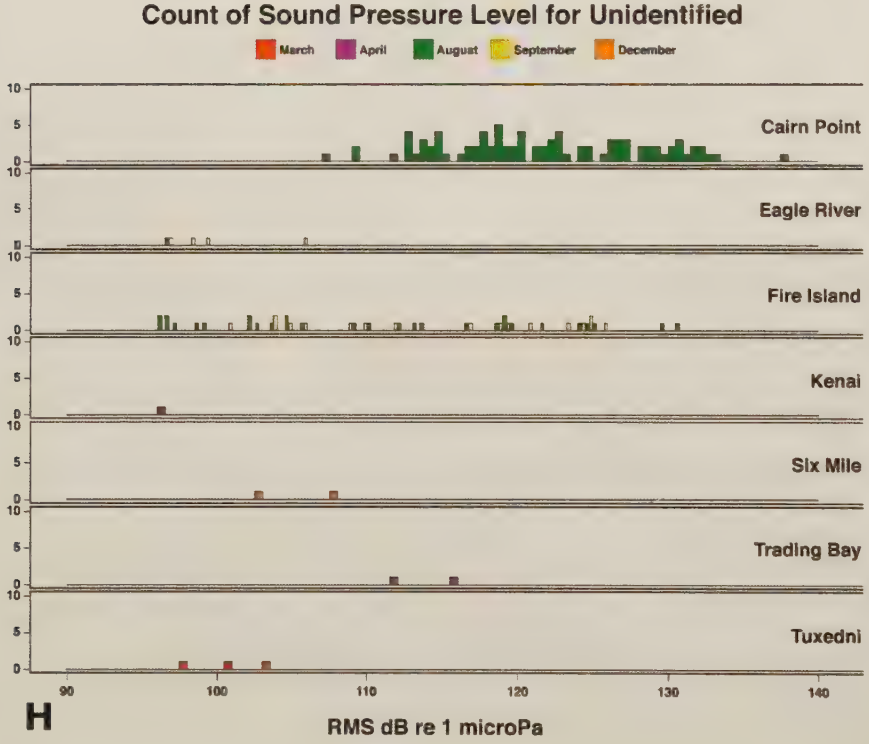
[17]Mahoney, B. NMFS Alaska Regional Office. Personal commun., 14 March 2016.





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127.2 dB peak, 107.4 dB_{rms}, and 120.4 dB SEL. Maximum levels reached 134.7 dB peak, 111.5 dB_{rms}, and 141.1 dB SEL (Fig. 4F).

The north extension of the POA involved impact piling of 14-inch by 90-ft long, steel H-piles. Piling was detected 18 km away (Fire Island) with mean received levels of 128.1 dB peak, 103.1 dB_{rms}, and 118.6 dB SEL, reaching maximums of 131.4 dB peak, 117.2 dB_{rms}, and 140.8 dB SEL (Fig. 4F).

Even if most of the acoustic energy radiated by the pile strikes was at low frequencies (below 1000 Hz; Fig. 5F), received spectral levels for both piling operations exceeded beluga hearing thresholds at the 4 kHz band and higher (Castellote et al., 2014). Vibratory pile driving was also used in these two operations but was not identified in the recordings and was likely classified as unclassed machinery. For the POA piling, a sound source verification was made in 2008, obtaining a worst case source level of 200 dB (Scientific Fishery Systems, 2009). Impact piling propagation loss would correspond to 22.8 x log (range in m) to obtain our received levels at Fire Island. Assuming constant propagation loss conditions across the arm, and worst case for source level for the impact pile driving, the 125 dB isopleth distance would be situated just passed the east shoreline across the port (2910 m) at the narrower part of the arm. Therefore, most of the width of the arm was likely ensonified to levels exceeding the behavioral threshold during this pile driving operation. A second acoustic study was made in 2009 yielding similar source levels, but the obtained propagation loss conditions were much less restrictive, 16.4 x log (range in m) (Širović and Saxon Kendall[5]). Using this propagation loss, the 125 dB isopleth would be reached at 37.5 km from the source.

These results suggest that sound propagation conditions, at least in the lower region of Knik Arm, are very complex and difficult to predict. But the concerning thought here is that the acoustic disturbance generated, beyond

the injury and behavioral harassment levels required to be monitored, often includes a vast region of beluga critical habitat. This is of special concern in constrained habitat areas such as Knik Arm. No passage might remain free of acute acoustic disturbance exceeding the behavioral threshold of 125 dB for transiting belugas, where pile driving operations have been ongoing for multiple years (2006–11, and 2016) as part of the POA Marine Terminal Redevelopment Project. The more recent POA modernization project, where months of pile driving are expected for multiple consecutive seasons starting in 2020, is one more case where unavoidable behavioral harassment, and its cumulative effects, should be taken into consideration.

Sub-bottom Profiler

Transducer generated sweeps from a sub-bottom profiler were detected at the Fire Island deployment location for more than 9 consecutive hours on 19 August 2009 (154 dB peak, 128 dB_{rms}, 173 dB SEL) and in Kenai for 3 hours on 1 April 2012 (124 dB peak, 105 dB_{rms}, 119 dB SEL). Mean sweep duration was 0.042 sec (standard deviation 0.015) but often with intense reverberation lasting up to 0.2 s, and the sweep started at 1 kHz and ended at 4.5 kHz, corresponding with the 1/3 octave bands of highest received spectral levels. Received spectral levels at these frequencies all exceeded beluga hearing thresholds (Awbrey et al., 1988; Castellote et al., 2014). The activity at Fire Island was related to a survey for a marine renewable energy project; however, the survey in Kenai has not been identified by NMFS. Received levels reported at Fire Island, considering that time intervals between sweeps are included in the SPL calculation, suggest that this activity ensonified a wide area with levels exceeding the behavioral harassment threshold of 125 dB_{rms}. Furthermore, this noise class also suffered clipping, another reason to consider received levels reported here as very conservative.

This noise class, together with some events of commercial ship noise, are

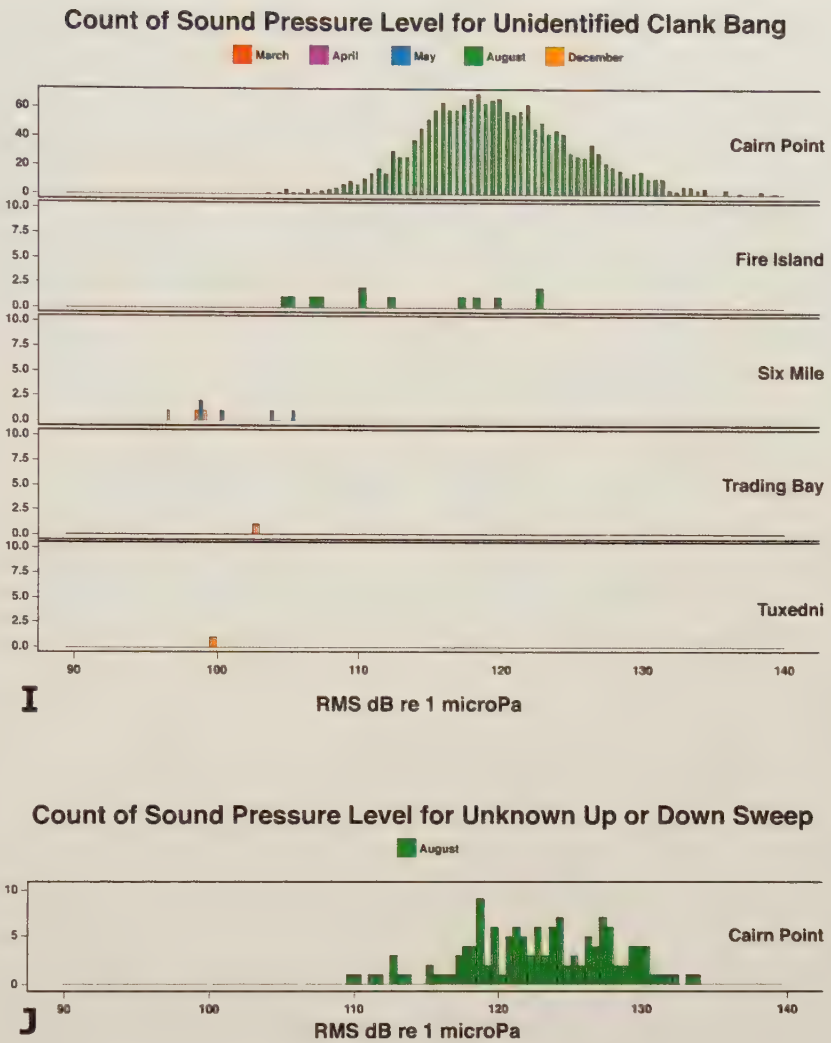


Figure 4.—*Continued.*

the highest amplitude anthropogenic noises detected throughout the data analyzed in this study, highlighting the relevance of the acoustic disturbance generated by sub-bottom profilers.

Helicopter and Propeller Aircraft

These two sources of noise had transient signatures that did not dominate the soundscape in the months and areas sampled (Table 2), thus, they are not discussed here. For details on these detections see Castellote et al.[13].

Unclassed or Unidentified Sources

The amount and prevalence of unidentified or unclassed noise events was surprisingly high in our dataset. As in any environmental acoustic study, unknown transient sounds are detected and cannot be identified without concurrent visual information. However, in Cook Inlet, many of these unknown signals are repetitive, very stereotyped (i.e., easily distinguishable with unique acoustic structure), and often repeatedly detected in the same locations for long periods of time. For example, 7.5% of the detections at Cairn Point were assigned to unclassed machinery with the longest durations of any anthropogenic event (mean duration of 6.1 h), and 50.7% were assigned to unidentified clank or

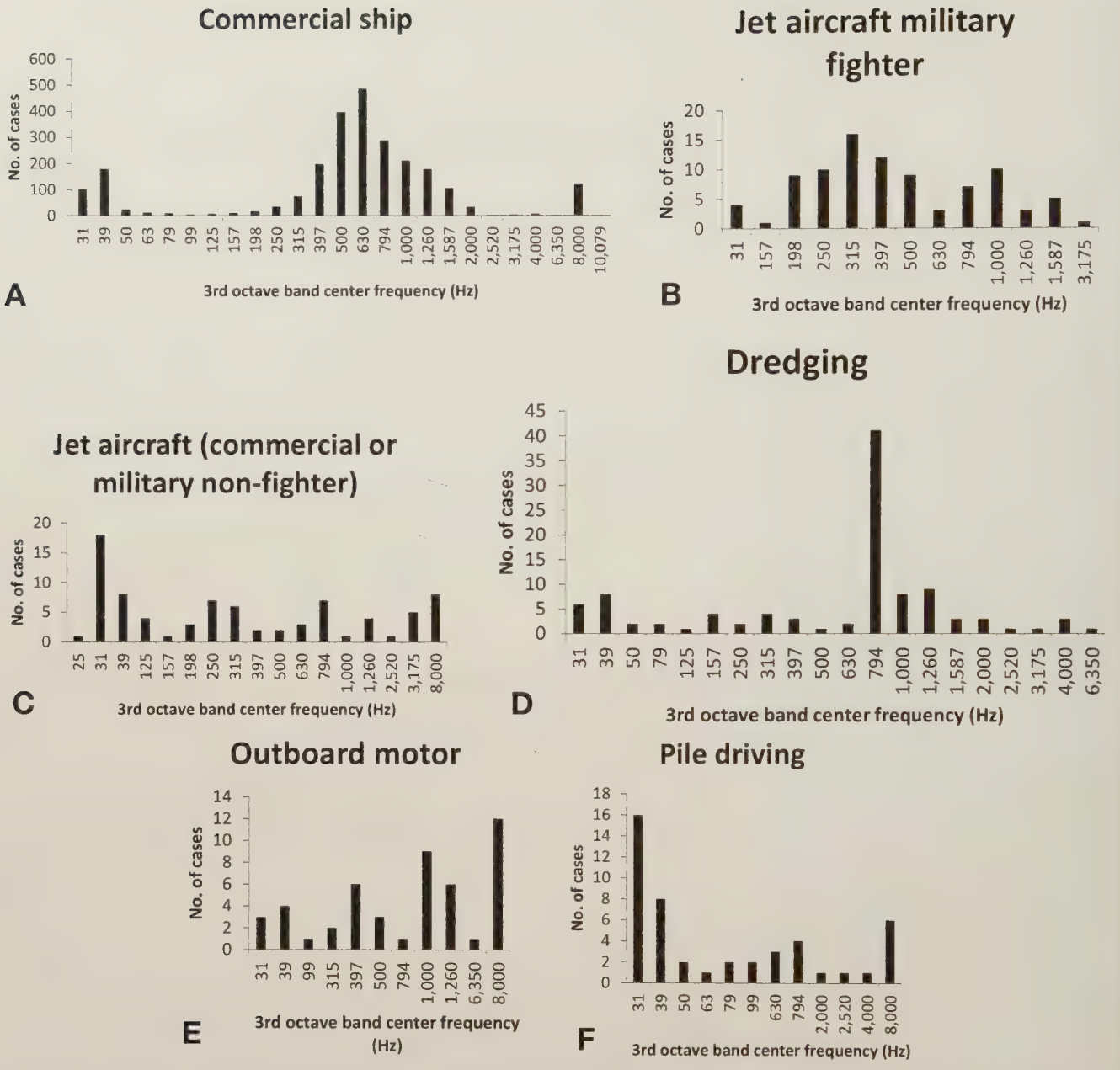


Figure 5.—Histograms with counts of 1/3 octave bands containing the maximum amplitude (peak band) per noise class. This histogram provides an overview of the dominant 1/3 octaves for each noise class identified in the sampled locations in Cook Inlet, Alaska. Noise classes included are, A) commercial ship, B) jet aircraft military fighter, C) jet aircraft (commercial or military non-fighter), D) dredging, E) outboard motor, and F) pile driving. For all other noise classes see Castellote et al. (2016c).

bang noise. All of these unclassed or unidentified noises exceeded beluga hearing thresholds at frequencies 500 Hz and higher (Awbrey et al., 1988; Castellote et al., 2014).

Together with Cairn Point, Trading Bay and Six Mile had the highest percentages of unclassed machinery and unidentified noise (6% and 53.9% of the total duration of anthropogenic noise events, respectively), and higher SPLs (means of 124.7 dB_{rms} and 123.1 dB_{rms} respectively, with a maximum reaching our recorders' upper limit of 144 dB_{rms}, Fig. 4G and 4H). Cairn Point and Six Mile are exposed to most of the noise derived from the industrial activities at the port facilities, the related shipping, as well as dredging activities in the port basin. Trading Bay included recurrent unidentified

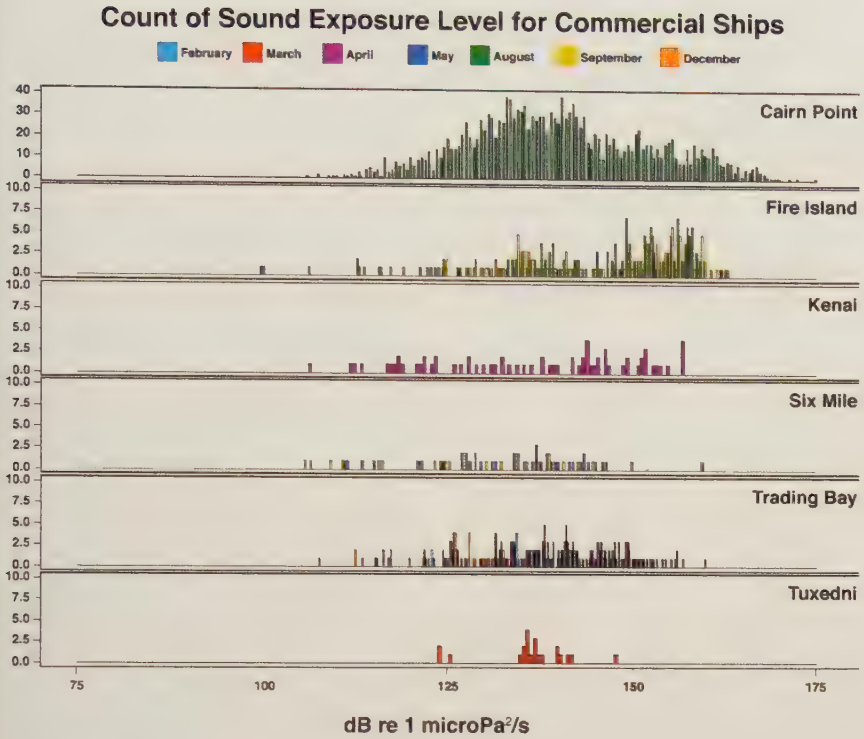


Figure 6.—Histogram with count of ship noise events per received level in SEL (dB re 1μPa²/s) showing the distribution of SEL, per month and location, from all events of commercial shipping noise detected in the sampled locations in Cook Inlet, Alaska. For all other noise classes see Castellote et al. (2016c).

noise with mean duration of 2 h that could be related to the oil and gas production activities from the multiple platforms and underwater pipelines in that location.

Similar to unclassed machinery and unidentified noise, unidentified clank or bang noise was a very prevalent noise class at Cairn Point, with the highest percentage of time of the total duration of anthropogenic noise events in this location (50.7%) and with mean longest sequence duration (Fig. 3) at Cairn Point and Fire Island. Some clank or bang signals appeared to be a cluster of multiple discrete impulsive signals, other times this noise was received as a rapid succession of multiple signals that could be the consequence of a sound propagation effect (e.g., multipath arrival) or a rapid iteration of the same type of percussive sound. This noise class often occurred concurrently with ship noise and might be related to shipping operations, where tug boats assist commercial vessels or barges and impact sounds are generated. The highest amplitude events occurred at Cairn Point (mean of 142.7 dB peak, maximum of 147.9 dB peak, Fig. 4I), followed by Fire Island (mean of 135.6 dB peak, maximum of 147.9 dB peak, Fig. 4I), and are likely a reflection of the proximity of the recorders to the area where these noises are generated, likely the shipping route. Clipping was also important for this noise class, therefore reported SPLs here are conservative.

Unknown up or down sweep noise was a very prevalent event (26% of all noise events) that occurred exclusively at Cairn Point (data from August 2010) with mean SPL of 117.7 dB_{rms} and maximum of 135 dB_{rms} (Fig. 4J). This noise class was concurrent with unclassed machinery and often occurred during changes in intensity of the related machinery noise or what was believed to be a reduction in rpm. It is not believed to originate from dredging operations (Anderson[14]), but because it was only detected in this location it was likely related to port activities.

Natural Background Noise in Cook Inlet

Our approach was to process the data to identify the periods with minimal presence of anthropogenic noise, however, inspection of the sound file selections corresponding to the higher sound amplitude periods confirmed that all the upper inlet locations included self-noise contamination (flow noise and debris hitting the mooring) in all months. Fire Island, Six Mile, and Cairn Point were the most affected locations by flow noise. The SPL histograms in Figure 7 show abundant RL conditions in the range of 120–130 dB_{rms} that correspond to tidal cycle periods of high current, when self-noise was predominant.

Background noise values for periods clean of anthropogenic noise were considered to be the natural background reference for each location for comparisons with anthropogenic noise contribution. Table 3 summarizes SPL results for each location and month. Mean dB_{rms} shown in Table 3 are below 120 dB_{rms} for all locations, even if some results suffered contamination by self-noise. Highest mean SPL reached 117.8 dB in Fire Island with 53.7% of the time exceeding 120 dB_{rms}, but this location is likely the one exposed to highest currents. If we exclude the three locations most contaminated by self-noise, SPL were below 120 dB for 94–100% of the time.

Percentile analysis reflected how daily noise varied considerably in Cook Inlet (Fig. 7). Differences greater than 40 dB can be observed within all sites from the quietest (10^{th} percentile) to the loudest periods (90^{th} percentile), which highlights how easily baseline background noise measurements in Cook Inlet can be misinterpreted if the full tidal cycle is not included in the sample and if self-noise contamination induced by high currents and vegetative debris is not considered.

Fire Island, Six Mile, and Cairn Point, the three locations of higher influence by currents, showed considerably higher noise levels across the full frequency range, but in particular in the range 0–1000 Hz and for the 50th and upper percentiles. Spectrum levels in these three locations never got close to those of Eagle Bay or Tuxedni Bay, the quietest locations, except for the highest frequencies, above 10 kHz. Cairn Point's spectral curves showed higher variability from 30 Hz to 1000 Hz suggesting the influence of low level, recurrent anthropogenic noise which was likely missed during the manual processing of the raw data.

The contribution of natural noise generated by high currents in upper Cook Inlet (air bubbles in the upper water column and breaking waves on shore, mud, and sand bars) will only affect the 0–1kHz frequency range (HDR[6]). Belugas have poor hearing below 1 kHz, with thresholds in the 100–120 dB range (Awbrey et al., 1988) that are above the noise levels obtained in this study. Even the highest levels of natural background noise (i.e. without human contribution) shown in Figure 7 never exceeded hearing thresholds for belugas (Awbrey et al., 1988; Castellote et al., 2014). Therefore, the contribution of natural noise by high currents has little relevance, if any, when considering the potential for masking on Cook Inlet beluga hearing and communication signals.

From this perspective, then, for belugas, the natural soundscape (i.e., without human influence) of Cook Inlet may not be a noisy environment. The upper Cook Inlet is considered a naturally high amplitude environment and thus acoustically poor (NMFS, 2008; NMFS[7]), but natural background noise might only be above beluga hearing thresholds during particular periods of elevated ambient noise (e.g., exceptionally strong current periods, storms, etc.). When SPL results from the locations in Cook Inlet that were minimally affected by self-noise (e.g., Eagle River, Tuxedni Bay, Trading Bay, Kenai River) are compared to other published results on underwater ambient noise, these are well below spectral levels reported for exceptionally quiet periods in open waters (Rolland et al., 2012), abyssal trenches (Barclay and Buckingham, 2014), or the Southern Ocean (Menze et al., 2017). Spectra and received SPLs for quiet locations in Cook Inlet are also below the estimated natural background noise levels in Saguenay Fjord in the St. Lawrence estuary, Can., which is critical habitat for another endangered beluga population (Gervaise et al., 2012; COSEWIC, 2014).

Interestingly, ice noise was not identified in any of the data sets analyzed for this study. Little is known on the noise production of new ice or first year ice. The elevated noise levels in some frequency bands identified during periods of natural background noise levels in winter (e.g., Fig. 7) could be related to noise generated by this thin ice. Further research is needed to better understand the effect of ice presence in the natural background noise conditions in Cook Inlet.

Noise Management Considerations

The results of our study support the thesis that anthropogenic noise carries a threat of high concern to the recovery of the Cook Inlet beluga population (NMFS, 2016). Recognizing current efforts to mitigate impacts to belugas from close-range noise sources in Cook Inlet (e.g., seismic surveys or pile driving), this study highlights the prevalence and diversity of many other anthropogenic noise sources occurring across a wide spatial scale within the critical habitat of Cook Inlet beluga whales. The acoustic characteristics of most of the detected noise events in this study have the potential to mask beluga hearing at certain frequencies and also their communication, and some exceed the current NOAA behavioral harassment thresholds on a daily basis.

Our results on natural background noise levels (i.e., without anthropogenic contribution or recording self-noise) do not support the current approach of using an elevated behavioral harassment threshold of 125 dB_{rms} for non-impulsive noise exclusively in the upper inlet. This approach, allowing a +5 dB over the 120 dB threshold defined by NMFS, has been applied to industrial operations since 2009, such as the POA Marine Terminal Redevelopment Project (vibratory piling) or Apache Alaska Corp. 3D seismic surveys (noise from vessels involved in the activity). A +5 dB difference in the threshold can be translated into an important decrease in the isopleth distance to be considered for the onset of behavioral harassment. This threshold appeals to stakeholders as it implies smaller risk of shut downs, power downs, or takes, and reduced areas to be covered visually for mitigation purposes.

Behavioral reactions need to be considered when background noise departs from natural noise conditions. The 120 dB threshold defined by NMFS for non-impulsive sources originated from research on migrating gray whales, *Eschrichtius robustus* (Malme et al., 1983; Malme et al., 1984). These authors documented behavioral responses to industrial noise playbacks depending on the characteristics of the signal-to-background noise conditions, comparing the playback received levels to the background noise levels just before and after the exposure. Reactions often occurred at ranges where the estimated level of the playback was equal to the local background noise level.

Both the work by Malme et al. and the threshold defined by NMFS are based on acoustic disturbances above natural ambient noise conditions and not from already altered acoustic environments which include anthropogenic noise sources. The background noise level to be considered for behavioral responses of belugas in Cook Inlet should correspond to the quiet undisturbed natural conditions, rather than conditions when other anthropogenic activities are altering the background noise levels (even if these are common). Similarly, inflated background noise levels due to recording artifacts, such as self-noise, from the often high current conditions in Knik Arm should

Table 3.—Mean, 1 x standard deviation in parenthesis, maximum and minimum received sound levels (SPL in dB_{rms} re 1 µPa), sample size in hours, and distribution of received sound levels in 120, 125, and >125 dB_{rms} bins, over the full band (0–12.5 kHz), for the sampled periods without anthropogenic noise at each location.

Location	Eagle River	Six Mile	Six Mile	Fire Island	Fire Island	Cairn Point	Trading Bay	Kenai River	Tuxedni Bay
Month	Aug-Sep 2010	Dec 2011	May 2012	Aug 2009	Sep 2009	Aug 2010, Apr 2011	Feb-Apr 2012	Apr 2012	Mar 2012
n (hours)	74.3	63.7	42.4	52.5	75.1	31.1	70.9	34.9	701.2
Mean dB	97.9 +/- 5.8	112.6 +/- 9.4	116 +/- 10.1	117.3 +/- 8.8	117.8 +/- 8.3	114.3 +/- 6.1	108.3 +/- 8.3	102.8 +/- 5.5	100.2 +/- 3.8
Max dB	131.9	134.7	136.7	134.2	136.5	142.5	126.5	118.2	
Min dB	95.2	95.3	95.7	95.5	95.6	99.3	94.9	95.0	
< 120 dB	72.6 h (97.6%)	48.7 (76.5%)	25.6 (60.4%)	20.7 (39.4%)	28.4 (37.9%)	26.7 h (85.8%)	66.8 (94.3%)	34.9 (100%)	70.2 (100%)
120–125 dB	0.8 h (1.1%)	8.6 (13.6%)	8.0 (18.8%)	25.8 (49.1%)	40.3 (53.7%)	3.0 h (9.7%)	4.0 (5.6%)	0	0
> 125 dB	0.9 h (1.3%)	6.3 (10%)	8.8 (20.8%)	6.0 (11.5%)	6.4 (8.5%)	1.4 h (4.5%)	0.1 (0.1%)	0	0

not be considered as representative of the natural environment.

Our upper inlet results show that natural background noise SPL values are below 120 dB in all sampled locations for most of the sampled time, except at locations exposed to strong currents, and mean SPLs are below 120 dB in all locations (Table 3). Therefore, the increased behavioral harassment threshold, by +5 dB, for non-impulsive noise in the upper Cook Inlet is not justified.

Two recent studies support the notion that upper Cook Inlet background noise is not as elevated as previously described. First, Burgess (2014) measured background noise levels in Turnagain Arm, an area within beluga critical habitat, with previously no reference for noise levels due to the difficulty of monitoring in the shallow waters, the highly dynamic bathymetry of the area, and the presence of extreme bore tides. Based on drifting recordings over a relatively short time period (40 sec to 4 min) in the range 19 Hz to 9.3 kHz, Burgess (2014) reported an SPL range from a low 74 dB at slack tide to a high 108 dB at flood tide. Second, Austin et al. (2016) measured background noise in the range of 10 Hz to 64 kHz during 3-day deployments at 2 POA monitoring locations, on the dock and 0.5 km off the dock, while routine port activities occurred, and reported median SPL of 117 and 122.2 dB. However, mean SPL for the same periods were 138 and 136 dB, respectively, highlighting the strong influence of transient elevated sound periods from routine POA activities on mean SPL values.

Austin et al. (2016) stated that dominant sound sources, from dredging and tugboat activities, occurred throughout the recording. They also reported periodic bursts of elevated sound levels likely caused by flow noise during maximum current flow, and brief peaks of broadband, high amplitude sounds attributed to tug activities and other normal vessel activities at the port, which matches our unidentified clang or bang class. Interestingly, high sound levels with tonal structure were attributed by these authors to dredging noise at the north end of the port. These signals might be the same ones we classified in our study as unknown up or down sweeps that were detected only at Cairn Point.

The results obtained at Cairn Point are particularly concerning. Cumulative effects of multiple sources of noise in this area of Knik Arm should be taken into consideration when evaluating threats and lack of recovery for Cook Inlet belugas, in particular negative effects related to spatial displacement. Results from Cairn Point represented some of the highest anthropogenic noise levels, prevalence, and diversity of both identified and unidentified noise sources.

Acute noise disturbance was caused by pile driving operations from several projects: the multi-year Marine Terminal Redevelopment Project, and maintenance and repairs of damage from ice at the POA, Port McKenzie, and the tug and barge facilities. These acute disturbances were combined with chronic noise from the regular shipping operations from both port facilities and the seasonal dredging of ~1,650,000 m^3 of silt required to maintain an operational depth of -35 ft at the POA (Hoffman, 2012).

Cumulatively, these factors result in a consistently high acoustic disturbance of the lower Knik Arm habitat. Using an elevated behavioral threshold of 125 dB_{rms} for non-impulsive noise sources should be reconsidered. Permit applications are typically considered on a case-by-case basis, but the spatial and temporal overlap among activities in our results indicate that the cumulative or additive increase in noise disturbance should be factored into the permitting process.

As part of the critical habitat designation (NOAA, 2011), NMFS defined an exclusion zone covering the POA and waters of Knik Arm in front of the port (i.e., turning basin; depicted in Figure 1). This decision was based on impacts to national security, because the POA supports certain military functions and requirements that cannot be met elsewhere in Alaska. Also, certain non-military functions that support the operational readiness of the port, such as maintenance dredging, could impact military operations if they were delayed or otherwise impacted by the designation.

Following the requirements of Section 4 of the Endangered Species Act (USFWS[18]), based on best scientific and commercial data, NMFS determined that the benefits of this exclusion zone outweighed the benefits to belugas without the zone. However,

[18]USFWC (U.S. Fish and Wildlife Service). Endangered Species Act, Section 4. Available online at https://www.fws.gov/endangered/laws-policies/section-4.html.

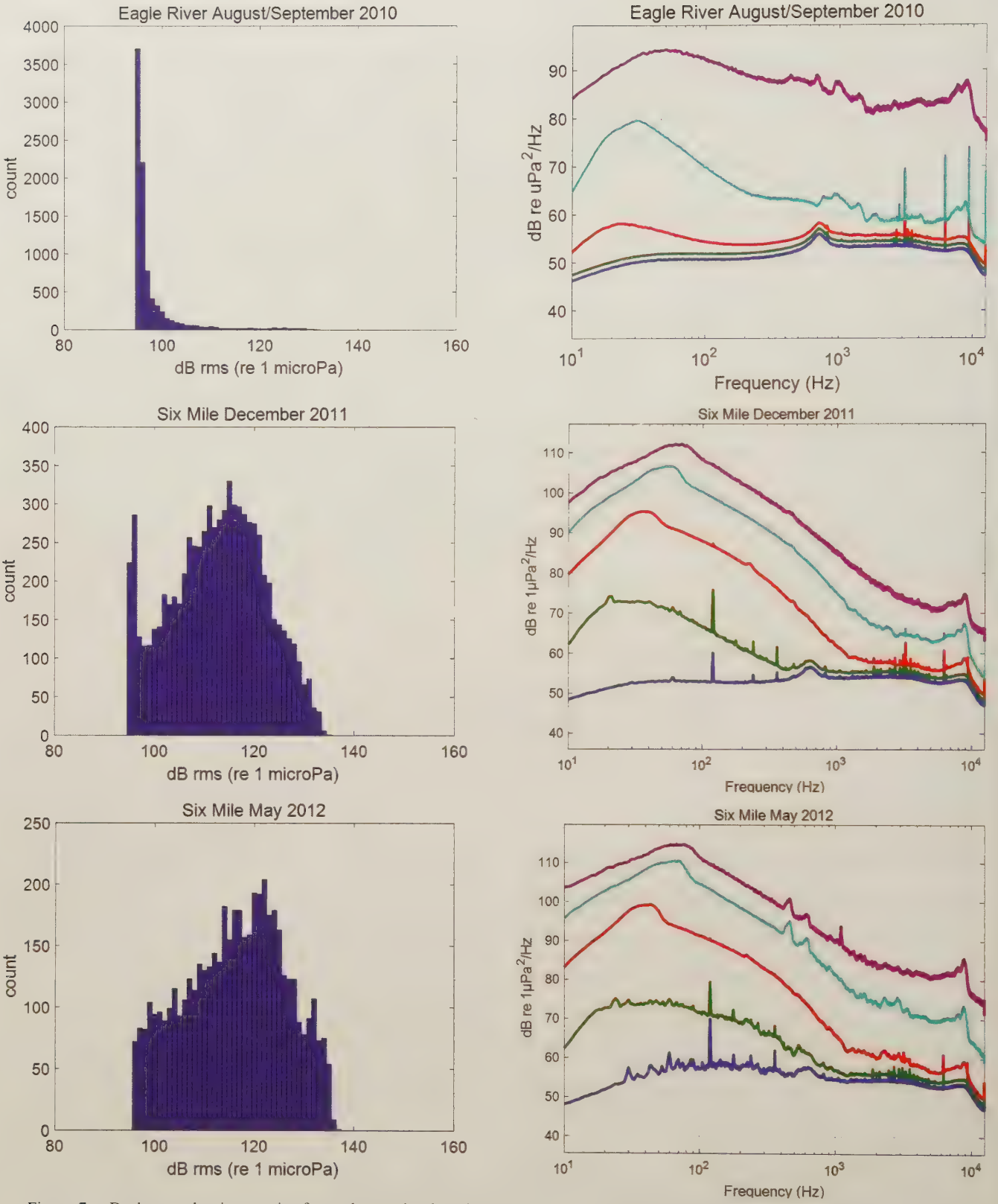
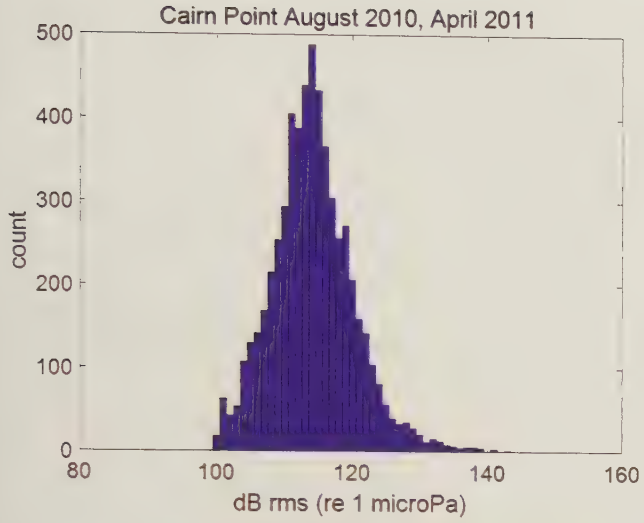
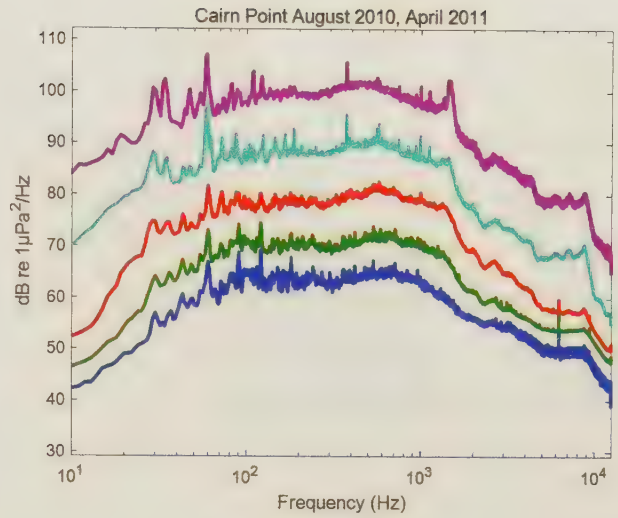
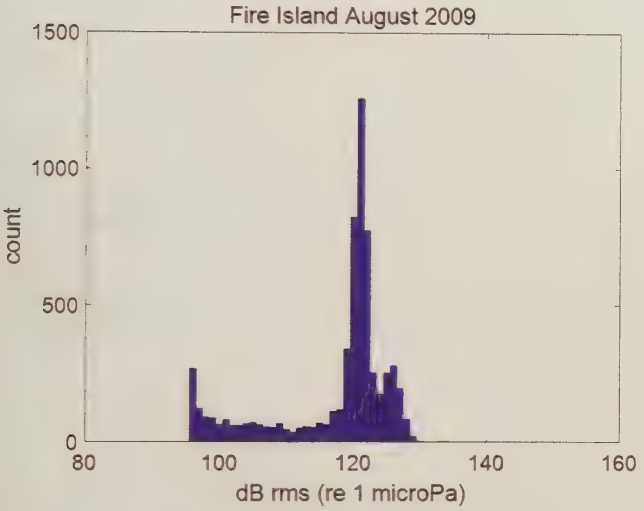
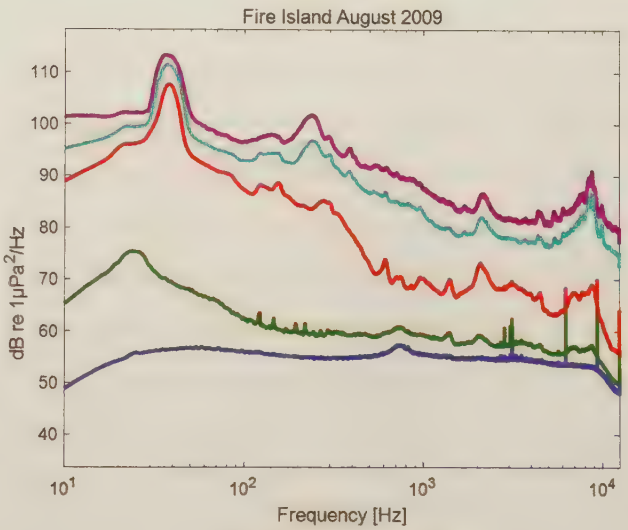


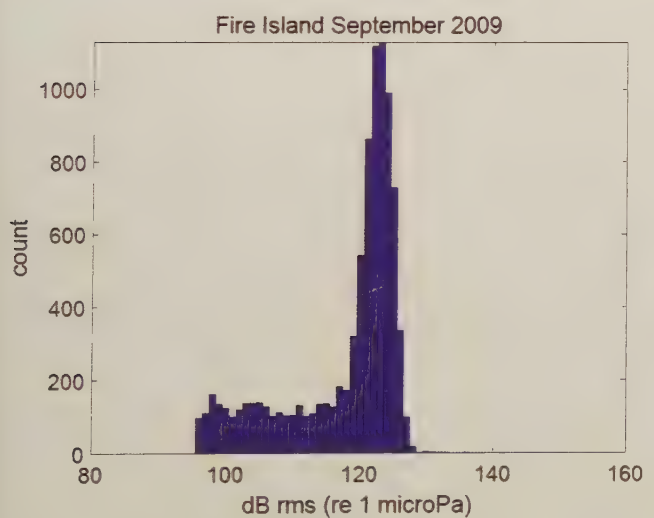
Figure 7.—Background noise metrics for each mooring location and month, obtained from periods without any visible anthropogenic noise signal in the spectrogram analysis. Left: Histograms of Sound Pressure Level (SPL) over the full band of the recording (0.01–12.5 kHz) in 1 dB bins for 5 min periods. Right: Power spectral density percentiles (blue = 1%, green = 10%, red = 50%, light blue =90%, and purple = 99%).

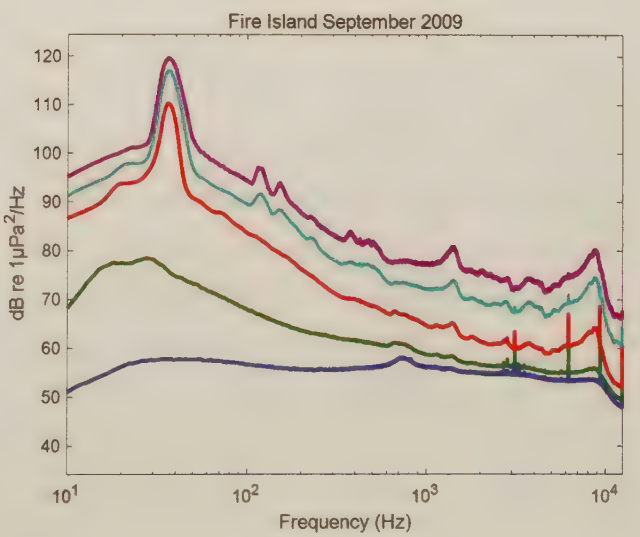












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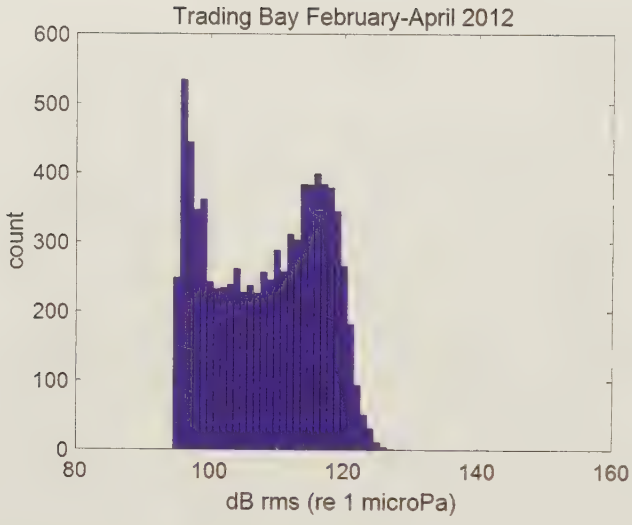

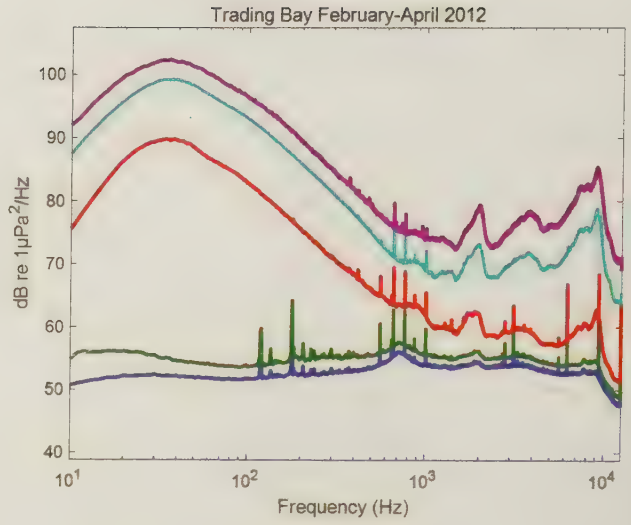

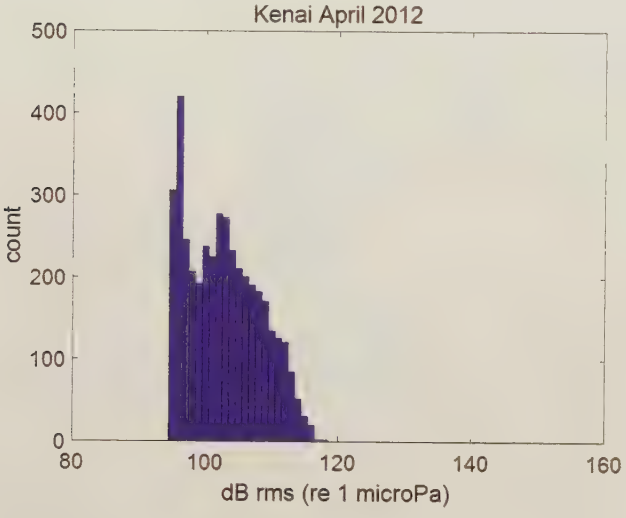

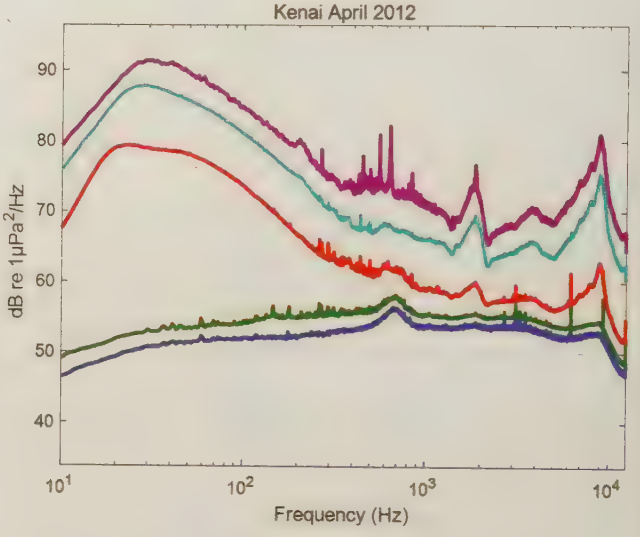

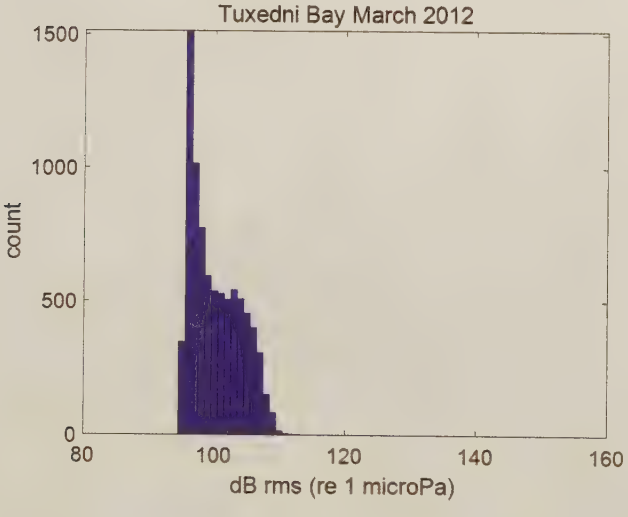

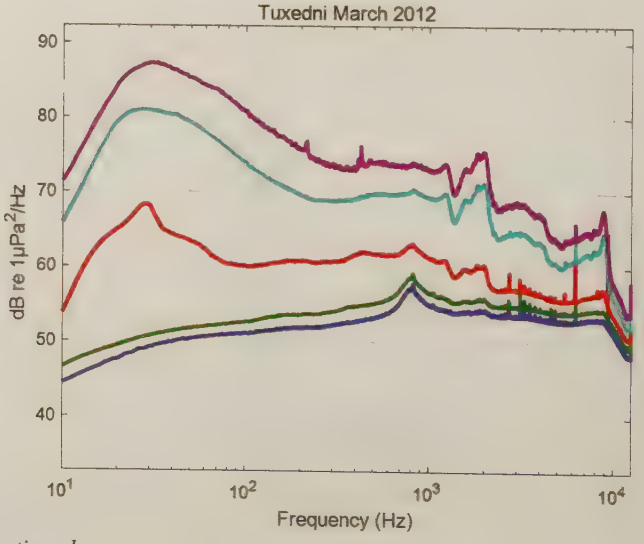

Figure 7.—*Continued.*

the exclusion zone coincides with the highest acoustically disturbed area of all the sampled locations in our study.

In the decision process, NMFS considered the small size of the exclusion zone, less than 1% of the habitat designated, and deemed unlikely that most Department of Defense activities associated with the POA or its operational readiness would require consultation on critical habitat because the activities should not affect that habitat or the identified essential features. Two of these essential features important to the conservation of the Cook Inlet beluga whale were defined as 1) unrestricted passage within or between the critical habitat areas, and 2) the absence of in-water noise at levels resulting in the abandonment of habitat by Cook Inlet beluga whales. Based on a small subsample of the data from Cairn Point, our results highlight the magnitude of the acoustic disturbance in the exclusion zone from activities related to the POA or its operational readiness, including commercial vessel noise (i.e., tugboat and barge operations), dredging noise, pile driving noise, outboard motor noise, as well as all four classes of unidentified noise (unclassified machinery, unidentified clanking or banging, unknown up- or down-sweeps unique to this location, and other unidentified sounds).

Although some of these upper inlet acoustic disturbances have the potential to generate direct impact to Cook Inlet belugas by exceeding injury thresholds, the main concern is the potential for behavioral responses to regulated (e.g., pile driving), regulated but non-mitigated (e.g., dredging), and non-regulated (e.g., shipping) sub-lethal noise exposure levels which occur year-round but at increased levels during the open water season when belugas use this area more intensely.

Beluga spatial displacement in this area of Knik Arm has been hypothesized as one of the explanations for a reduced sighting rate during pile driving seasons (Cornick et al., 2011), reduction in the acoustic detection rate during pile driving activity periods (Saxon Kendall et al., 2013), and on a regular basis due to chronic noise occurrence (Castellote et al.[13]). Displacement due to stationary high amplitude noise sources such as pile driving or dredging noise disturbance is a common behavioral reaction in other odontocete species (Tougaard et al., 2009; Pirotta et al., 2013), as well as to construction-related vessel traffic intruding into cetacean habitat (Anderwald et al., 2013), which could lead to long-term abandonment of the disturbed habitat (Morton and Symonds, 2002; Lusseau and Bejder, 2007). For Cook Inlet belugas, spatial displacement due to anthropogenic noise could not be ruled out in a recent study (Small et al., 2017). Therefore, spatial displacement by regulated as well as non-regulated activities might be occurring in this area of the beluga critical habitat.

The lower part of Knik Arm is an important concentration area for belugas (Rugh et al., 2010), as well as a corridor to access major foraging habitat within Knik Arm (Goetz et al., 2012). If belugas are displaced from this area, even if only within the exclusion zone, access to major feeding grounds in the upper sections of the arm could be compromised. With a Recovery Plan highlighting anthropogenic noise as a threat of high concern (NMFS, 2016) and the documented acute and chronic concentration of anthropogenic noise in the lower Knik Arm, potentially negative effects (e.g., displacement, abandonment) from noise exposure in this area should be considered a high research priority.

The amount of unidentified or unclassed recursive noise events, their received levels, and their long durations at Cairn Point, Six Mile, and Trading Bay are relevant and warrant discussion. We presume these events are related to dredging and shipping operations around the port facilities and oil and gas production and related operations in Trading Bay. The identification of their sources and the modes of operation responsible for the emission of these high amplitude events should also be considered a research priority.

Two noise activities were detected that should have been the subject of a permit request; however, they could not be matched with either NMFS or U.S. Army Corps of Engineers permitting files: Specifically, a sub-bottom profile survey and an impact pile driving operation were both detected at Kenai in April 2012. Occurrence of the two unauthorized activities within the relatively small sampled period for this study suggests that activities involving important acoustic disturbances within beluga critical habitat do occur without prior evaluation of their potential impact.

Sub-bottom profiler noise metrics obtained near Fire Island and Kenai highlight that this noise source should be considered an important acoustic disturbance for belugas. The survey in waters around Fire Island was made in August, at the peak of beluga concentration in this important feeding area (Shelden et al., 2015). The survey in Kenai was detected in April, during the only period when this area is visited by belugas on an annual basis (January to April, Castellote et al.[8]). Apparently, beluga seasonal distribution was not considered when these surveys were planned, and avoiding disturbing these areas during periods important for belugas would be relatively easy.

Kenai was exposed to intense outboard motor noise in April, which might be related to preparations for the important fishing activities in that area. Our study did not include data from the summer months in Kenai, when most of the commercial, sport, and subsistence fishing occurs, but our April results suggest that outboard motor noise in this area might peak during the summer. This area has historically been intensely used by belugas from April to November (Huntington, 2000), a period when anadromous fish are likely available in high concentrations.

Currently however, beluga appear to prefer February to April for the Kenai river mouth (Castellote et al.[8]), coinciding with the first anadromous fish runs (whitefish, *Coregonus* sp.; and eulachon); yet, sightings in June, September, and October have also

been reported (McGuire et al., 2014). Huntington (2000) discussed how the increase in human activity may have affected beluga distribution and abundance in the river and the nearby waters of Kenai. The observed change in beluga seasonality, in particular the absence of belugas during the main summer fishing months (salmon runs), could be related to an increase in human disturbance (i.e., vessel presence and motor noise) during the fishing season. This potential displacement effect merits further research.

Recommendations and Conclusions

Our results document the high and variable nature of anthropogenic noise disturbance in Cook Inlet beluga critical habitat. Specifically, there is strong variability in source diversity, spatial distribution, and seasonal occurrence of noise, which reflects the many different human activities within the inlet. Some activities clearly deserve further attention, in particular those that in the past were not considered to affect beluga critical habitat or the identified essential features but that might be relevant to the recovery of the Cook Inlet beluga population. In this regard, if a revision of the critical habitat designation were to be considered, the spatial extent of the current exclusion zone and inherent implications for anthropogenic noise management would be warranted.

Commercial shipping is the noise source of highest priority for evaluation due to its reported noise levels, prevalence, and wide spatial distribution throughout the critical habitat. Mitigation of ship noise in other major harbors and ports overlapping with cetacean critical habitat already exists. The best example is at the Vancouver Fraser Port Authority (Canada), within the critical habitat for the endangered southern resident killer whale population. In 2014, the Port Authority launched the Enhancing Cetacean Habitat and Observation (ECHO) Program, designed to better understand and manage the impact of shipping activities on endangered killer whales and other cetaceans throughout the southern coast of British Columbia, and to develop mitigation measures to reduce potential threats. This program and other actions were implemented to characterize and subsequently reduce the acoustic threat from impacts of cumulative vessel noise (Vancouver Fraser Port Authority, 2016).

The area between the POA and Port McKenzie in lower Knik Arm is highly disturbed acoustically due to the convergence of different sources of noise. Because this area is geographically constrained, there is considerable potential for generating a barrier that reduces passage by belugas. A detailed analysis of the activities at the different port facilities in the context of noise production would provide insights on how to minimize this problem, and should include at least the following: 1) avoiding concurrent emission of noise at both the POA and Port McKenzie, 2) evaluating seasonal dredging of the port basin to gain an understanding of the acoustic footprint from different dredge types and under different modes of operation, 3) conducting behavioral observations of belugas to assess their reactions to dredge activities and subsequently define shut down protocols, if necessary, and 4) seasonal scheduling to reduce overlap with beluga peak use of the port basin.

Two important features of the Cook Inlet soundscape highlighted in our study are relevant to current noise management procedures. First, the SPL for natural background noise does not support the current 125 dB_{rms} threshold for non-impulsive noise sources. Second, the spatial and temporal overlap of different high amplitude anthropogenic sources of noise, in particular in the Knik Arm area, calls for the implementation of a cumulative impact analysis approach as part of the permitting process. Perhaps a fixed share system for takes (i.e., quota) per season, or a coordinated scheduling and prioritizing of all noise producing activities during the permitting and planning process, could integrate the different activities proposed each season in beluga critical habitat to minimize cumulative impacts.

The Kenai River fishing industry has been largely ignored within the framework of Cook Inlet beluga conservation in part because this activity is seasonal, highly spatially concentrated, and the reduction of prey due to fishing is not of high concern for Cook Inlet beluga recovery (NMFS, 2016). However, the footprint of acoustic and physical disturbance at the mouth of Kenai River could be considerable and overlaps with the historical occurrence of belugas in this river. Determining whether belugas have been displaced by fishing activities from this previously important feeding area should be considered a management priority.

Our results suggest that the amount of unidentified or unclassed but repetitive anthropogenic noise warrants special consideration to identify those sources that might require further regulatory control. Concentrated oil and gas production in the Trading Bay field and shipping activity at the port facilities in lower Knik Arm deserve a closer look in this regard.

The detection of unpermitted actions, such as pile driving or sub-bottom profiling operations in the Kenai river mouth area, suggest that authorities should strengthen enforcement and outreach efforts to reduce the negative impact of underwater noise on the recovery of the beluga population. For example, the development of underwater noise reduction incentive programs could be considered for different industries, such as the multiple programs in place for airports, or the recently started program for the Port of Vancouver, Can. Also, further acoustic monitoring in areas where human activities occur or are expected should be supported as it would help understand the scope of this problem.

Much work remains to understand and reduce the acoustic impact to Cook Inlet belugas. Many sources of noise remain unidentified that may be relevant contributors to the disturbance of the critical habitat soundscape. Other noise sources are now known but have typically been excluded from control and regulation, in part because of the inconvenience and lack of quan-

tified measurements. Acute noise-producing activities such as pile driving or oil and gas exploration are subject to strict noise impact evaluations and include marine mammal monitoring and mitigation programs; however, the spatial or temporal accumulation of noise from other sources, and the concurrent exposure to other stressors, are not considered.

Clearly, Cook Inlet waters host a high concentration of human activities that is reflected in the magnitude of noise disturbance documented in this study. The management and research recommendations presented here are consistent with many of the recovery actions proposed in the recovery plan (NMFS, 2016), and represent a first urgent step towards understanding the effects of anthropogenic noise on the endangered Cook Inlet beluga population, and how to manage those effects to promote beluga recovery.

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Keep titles, headings, subheadings, and the abstract short and clear. Because abstracts are circulated by abstracting agencies, it is important that they represent the research clearly and concisely. Headings within each section must be short, reflect a logical sequence, and follow the rules of multiple subdivision (i.e., there can be no subdivision without at least two items).

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The entire text should be intelligible to interdisciplinary readers; therefore, all acronyms, abbreviations, and technical terms should be spelled out the first time they are mentioned. The scientific names of species must be written out the first time they are mentioned; subsequent mention of scientific names may be abbreviated. Follow the U.S. Government Printing Office Style Manual (2008 ed.) and the Scientific Style and Format: the CSE Manual for Authors, Editors, and Publishers (2014, 8th ed.) published by the Council of Science Editors.for editorial style, and the most current issue of the American Fisheries Society's Common and Scientific Names of Fishes from the United States and Canada for fish nomenclature. Only journal titles, scientific names (genera and species), and vessel names should be italicized. Dates should be written as follows: 11 November 2013. Measurements should be expressed in metric units, e.g., metric tons as (t); other equivalent units may also be listed in parenthesis. Common abbreviations and symbols such as mm, m, g. ml, mg, and °C (without periods) may be used with numerals. The numeral one (1) should be typed as a one, not as a lower-case el (l). Write out the numbers zero through nine unless they form part of measurement units (e.g., nine fish but 9 mm).

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